THE ACOUSTIC PROPERTIES OF TEXTILE FABRICS

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by

Mahabir Singh Atwal

under the supervision of Dr. B. Schofield

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Sponsoring Establishment

Leicester Polytechnic,
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Rola Celestion Limited,
Ipswich, Suffolk,
England.

THE ACOUSTIC PROPERTIES OF TEXTILE FABRICS (M.S. ATWAL)

ABSTRACT

A thorough understanding of the sound wave propagation properties of porous materials such as needle-felted fabrics, is becoming increasingly important because of their wide variety of unusual and important applications, such as high-fidelity loudspeaker covers and noise attenuating partitions. A simple and useful theory is presented in this work for predicting the acoustic properties of porous materials. The main thrust of the research is directed towards the determination of acoustic transmission loss as a result of the needle-felted material being present in a sound path, so that ultimately it is possible to predict the optimum characteristics required to produce the most and the least efficient acoustic absorbent.

The initial theoretical part of the work includes the derivation of the general sound wave equation, which takes account of: the presence of air and solid matter in each unit volume of space; the viscous friction between air and fibre surface; and the conduction of heat as a result of fluid compression. The general sound wave equation from which the inter-relationship between transmission loss and certain properties of the material is derived, is obtained by solving simultaneously the equations of continuity, state and motion. These equations describe the change of particle velocity, density of the medium and sound pressure.

The subsequent experimental part of the work involves the manufacture of needle-felted fabrics from parallel-laid webs, and testing these fabrics for their acoustic transmission loss on a specially designed acoustic test rig.

In general it was found that the acoustic transmission loss increased with the frequency of the sound, and with any fabric parameter that changed the microstructure of the fabric in such a way as to increase the air flow resistance or decrease the porosity, the most significant factor being the total exposed fibre surface area in the sound path.

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CHAPTER ONE

INTRODUCTION

1.1. General Introduction

We live in a world of sound. Sound plays a part in our daily lives scarcely less important than light and motion, and the sense of hearing though by no means considered as precious as the sense of sight, is yet so prized that the production of efficient hearing aids for the deaf is a major industry. No other form of energy so pervades every facet of our living. It is the primary medium for communication and without sound the continuous transfer of knowledge of the world around us would almost disappear. Sound requires no line of sight contact, and unlike our eyes our ears are never closed. Sound is being received literally by the ear at all times and this fact alone accounts for the many occasions on which sound is superior to other forms of communication. We hear only the signals for which we are listening, even though we may be enveloped in a sound field that is produced from dozens of sources. For example on a busy street we can engage in a meaningful conversation, even though superimposed upon this conversation may be the noise of traffic, the roar of a jet flying overhead, the sound of construction work, or the output from a transistor radio.

Since the beginning of this century the study of acoustics has increased its bulk and scope enormously as a consequence of the development of new methods of investigation. On the one hand the range of frequencies with which the subject formerly was concerned has extended into regions beyond audition-into the supersonic regions and also into that of very low frequency pulses. On the other hand acoustics has entered into a new area, called electroacoustics, which is based on the telephone and its lineal descendant the loudspeaker. The advent of these novelties has been expedited, perhaps even provoked, by the attention given to acoustics during the war. But perhaps the chief single cause of the practical importance now accorded to acoustics is the rise of broadcasting. This relatively new popular diversion greatly has extended and altered the study of acoustics; it has diverted acoustical study from a limited academic path on to so-called practical lines. That is to say, the study of acoustics is now most keenly pursued, not for its intrinsic scientific interest alone, but also because of its utilisable results.

In explaining the waves of interest in acoustics that have been generated since the begining of mankind, it is perhaps appropriate to begin with the oldest of all acoustical receivers-the ear. The subject of the ear by no means has been explored completely. However, evidence of the interest being shown is in the award of the Nobel prize in Physiology or Medicine to George Von Bekesky in 1962 for his discoveries concerning "the physical mechanism of stimulation within the Cochlea". Von Bekesky was a physicist who began his career with the Hungarian Telephone Company and finished it in the Harvard psychology department. He attempted to understand the coupling of the telephone system with the human ear. This led him to delve into the operation of the ear itself, and to create numerous mechanical and electrical models of the ear, and more especially of the Cochlea.

The human ear because of its intricate construction of levers, diaphragms, canals, membranes and hair cells, can detect sound over a vast range of intensities and frequencies[1,2]. It can hear sounds the loudest of which can be ten billion times as intense as the softest. Similarly, the ear can analyse sounds over a range of frequencies, with the highest almost a thousand times greater than the lowest. The human ear is capable of hearing sound waves having frequencies from about 20Hz to 20kHz. The threshold of hearing (defined as the sound pressure at which a person, listening with both ears in a free field can still just hear the sound) is very much frequency dependent[3]. In general two tones of equal sound pressure but different frequencies are not heard equally as loud.

The ear is a very senstive organ, and quite apart from the possibility of damage from natural causes such as disease, the hearing mechanism can also suffer from exposure to high levels of sound which may impair hearing and even result in a permanent hearing loss. If the high level of sound is of a particular frequency[4], it can produce deafness over a range around that frequency.

The ear acting as a senstive sound receiver presents problems to many industries. It's ability to analyse sounds of a vast variety and intensity is a problem to high fidelity equipment manufacturers, who are updating their equipment all the time in order to achieve "perfect" reproduction. The possibility of damage to the ear as a consequence of exposure to high levels of sound also can be a problem to some manufacturing industries where there is considerable noise in the working environment.

1.2. The Loudspeaker Cover Cloth Problem

In relatively short period, radios, tape recorders, recordplayers, televisions and so on have become essential commodities, and at present most homes in Britain have at least a few of these machines. The continuing popularity of such instruments can be attributed to the fact, that, they are a simple and economical vehicle for effecting an instant change in the environment, thus satisfying man's seemingly insatiable appetite for transiency. It is evident that these instruments can offer this change even if all other environmental factors remain constant. Clearly with the increasing output of radio, and television sets, the demand for loudspeakers also has increased.

An essential objective in the design of high quality loudspeakers is to obtain reproduction which requires the minimum use of imagination by the listener. In other words the listener should be made to feel as if he were actually present at the concert and so the reproduction effort must be directed towards capturing the acoustical environment of the concert hall itself. Over the last seventy years, loudspeaker design has not shown the same rate of progress as that experienced in other fields of telecommunication. Loudspeaker development has not suffered for want of effort. The patent files are evidence of the fact that every variable has been varied. Moreover, further variables have been added and these too have been investigated. Unfortunately, in the enthusiasm to explore every avenue, the sense of direction sometimes has been lost, and some of the fundamental issues overlooked.

The loudspeaker drive unit is an expensive and vulnerable item and as such has to be protected from dust and physical damage. Moreover, usually it is considered to have no great aesthetic appeal and therefore both the protection and decoration requirements can be fulfilled by using a textile fabric cover. There is considerable interest in the type of fabric to be used because when a cloth is placed in front of a loudspeaker, listening tests invariably indicate that the speech and the music reproduced sounds are somewhat 'muffled' and 'hollow' and are lacking in presence. While the transmission loss of the cloth may be very small, the difference in the reproduced sound between a speaker without a cloth and a speaker with one is very pronounced, particularly at high frequency. Initially, woven fabrics were employed as speaker covers since they afford adequate protection coupled with good drape characteristics. More recently interest has been shown in knitted fabrics because of their ability to follow the complex contours of a detailed grill-board and their more intrinsically 'open' structure. Intuitively, it is the openness of the structure that should influence transmission of sound through the fabric. Hence the fidelity characteristics of even the 'best' loudspeaker will be spoiled by the presence of a grill cloth of the wrong design.

1.3. The Noise Problem

At the same time as man was learning to create, and broadcast pleasurable stimuli to his sense of hearing, he was beginning to pollute his surroundings and blunt his hearing by making more and more loud and unpleasant sounds. Primitive societies today are predominated by the sounds of nature and characterized by their lack of man made sounds. In reality, all of the uproar concerning noise pollution is not new. Even as early as 44BC, Julius Caesar[5] is said to have expressed great displeasure at having his sleep disturbed by the noisy chariots traversing the streets of Rome at night. He therefore issued orders to have such activity restricted. Unfortunately, there are no subsequent records documenting Caesar's success with this order. It was the Industrial revolution in Britain which heralded the start of the age of noise. The new factories, mines and ironworks brought pollution of all kinds-smells, fumes and 'eyesores' and of course noise.

Noise can be defined[6] as audible sound which is conciously or unconsciosly resisted by the listener. This simple description emphasises the cardinal fact that noise is subjective; a noise problem must involve people and their feelings; and its assessment is a matter rather of human values and environments than of precise physical measurements. These values and environments are complex indeed. Not only do people vary in their susceptibility and adaptability to noise, but each of us may be annoyed by one noise but not by another of similar physical characteristics. A sound which most people would ignore, in, say the industrial part of the city, would be a disturbing noise in the country. The annoyance produced by a noise is often related to the information it conveys, or the association or emotion it excites, rather than to its actual intensity; and a sound of small intensity such as that from a dripping tap, may become unbearable simply from repetition. Thus whether a sound is a noise, or whether a noise is annoying, may depend upon many factors which are independent of its physical qualities. The physicist can measure the energies and the frequencies of simple and complex sounds. The psycho-acoustician can set up subjective scales of loudness with reasonable confidence. But it is impossible to foretell with any precision what an individual's reaction to a particular noise will be.

Health as defined by the World Health organisation "is a state of complete physical, mental and social well-being and not merely an absence of disease and infirmity". For the most part, people's well-being is diminished by noise, so in this sense of the term there is no doubt that noise affects health. The effect of exposure to noise on human health and well-being has been studied intensively, and many physiological and psychological ailments have been attributed to it. Even at low levels, noise may be annoying as it interferes with listening and concentration; while at the other extreme, very prolonged noise can result in temporary or permanent hearing losses[7-10]. Moderate noise levels over a period of time may interfere with normal functioning of nervous, digestive, circulatory, cardiovascular and endocrine systems[11-13], thus introducing a deterioration in general health. One very serious result of noise is loss of sleep[14]. Economically noise also can be detrimental. It has been shown that noise frequently has a negative effect on working efficiency[15], although sound has been shown to stimulate alertness and thus increase efficiency in some tasks[12].

High noise levels traditionally have been taken for granted by the textile industry. The broad-band noise of spinning and twisting machinery, and impact noise of looms long have been regarded as necessary evils of the trade. Early in the 1950's, a survey of industrial noise was conducted to assess the occupational hearing loss potential[16]. At that time, noise levels in the work areas of the textile industry seldom were found to be below 85dB and often exceeded 95dB. Much of the machinery in use today virtually is unchanged from designs of two or more decades ago. One obvious difference in textile operations of today, however, is that these same machines now run at significantly higher speeds. As might be anticipated, this trend towards greater speed has resulted in higher noise levels in some operations[17]. Despite the fact that spinners and weavers have been found to have significantly greater hearing loss than control population not exposed to similar noise levels[18-20], little progress has been made in quietening textile machinery. This may be attributed largely to the fact that, until the advent of noise control legislation, there was no emphasis on noise control. In Britain the first act of parliament that specifically focused on the noise abatement problem was the 1960 Noise Abatement Act, which widened the scope of part three of the Public Health Act of 1936. Noise abatement is one of the most acute problems of today.

Many of the steps that can be taken to control noise[21] can be taken whatever the noise source. This fact stems from the fundamental physical laws that govern the way sound propagates and from the common geography of any noise problem which determines the area in which control can be exerted. Firstly it might be possible to effect certain modifications of the noise source that will reduce the noise generated. This seems the most logical method; but is not always possible to do this. Secondly it is possible to reduce the noise by wearing protective devices such as ear-muffs. Evidently there is a limit to making full use of this property; and it is fortunate that there is a third method available. This involves the annihilation of the sound energy by means of barrier to the flow of energy in the path of propagation. In principle sound will be absorbed to some extent by a barrier of any material. Absorption of sound occurs when the energy in a sound wave is converted into either mechanical or heat energy. Barriers can be made from porous and non-porous materials. It is, for example, a well known fact that wooden panelling or a window pane absorbs sound by their ability to vibrate in resonance. Because of this the region of maximum absorption is located at lower frequency. The absorption by such a structure is dependent upon the frequency and mass and follows what commonly is referred to as the "mass law of sound insulation"(22).

As pointed out by Rayleigh(23), viscosity causes the acoustical energy to be transformed into heat. The absorption process, due to viscosity, may be enhanced to a great extent, if the wave does not travel freely, but is forced to proceed in narrow channels. Qualitatively, the reason for this is easy to understand; in narrow channels the gas adheres to solid walls and as consequence large transverse velocity gradients are set up with strong viscous forces resulting in considerable dissipation. Porous materials such as textile fabrics possess a large number of narrow channels and hence such fabrics will absorb sound as a result of this viscosity mechanism. A porous material, when used as a sound-absorbing layer attenuates sound waves partly by acting as a reflecting surface-as does a solid wall-and partly by converting to heat the acoustic energy of the sound that penetrates as a direct consequence of the viscous losses in the interstices. So effective are some porous materials(22, 24) that a sound wave at 1000Hz is attenuated 58dB in travelling 30cm. The mass surface density of a 'wall' of this material is only $2\,kgm^{-2}$. The mass of a solid partition necessary to provide this attenuation at 1000Hz would be over fifty times as great. At low frequency the situation is considerably different. For example at 250Hz the attenuation for a porous material of 30cm thickness would be 30dB, whilst that for a 100 kgm^{-2} solid wall would be about 43dB. Thus it would be advantageous to use porous materials rather than non porous when either:

(a) weight is a primary factor; or

(b) flexibility is desired as in the case of curtains; or

(c) control of noise at frequencies above say 500Hz is the essential requirement; or

(d) some combination of these factors must be satisfied. For example for the control of noise in passenger aircrafts, where both low weight and the improvement of speech intelligibility are dominant factors in the choice of porous materials as sound barriers at the cabin walls.

1.4. Aims and Objectives

In both cases discussed above, namely the loudspeaker cover cloth and the sound attenuating partition, sound waves from the loudspeaker cone or the noise source pass through a porous material. Part of the acoustic energy incident on the porous material will be reflected, part of it will be absorbed and the rest will be transmitted to the other side. However as far as the listener or the noise receiver is concerned the reflected energy also can be considered as having been absorbed. The acoustic transmission loss, which may be defined as 'the loss in detected acoustic energy due to reflection and absorption resulting from placing the porous material (loudspeaker cover cloth or noise attenuating partition) in the sound path' in this work will be investigated. Moreover the object of the work will be to formulate quantitatively a theory for the dissipation of sound in porous materials, so that a basis can be established for optimising and predicting their transmission loss. To this end, a high fidelity loudspeaker manufacturer, Rola Celestion was prepared to act as a collaborating establishment.

In chapter three a simple and useful theory will be presented for predicting the sound absorbed by porous materials. Sound absorption computed from this theory then will be compared with the experimental values, to test the validity of the theoretical work. Finally in chapter seven deductions will be made from the theoretical and experimental work for predicting the characteristics required for the two extremes, that is for the material having the lowest transmission loss (loudspeaker cover cloth) and the highest transmission loss (noise attenuating partition). To obtain a more fundamental approach, the porous materials used in this project will be nonwoven needle-felted fabrics.

1.5. Why Needle-Felted Fabrics

In textile manufacturing the aim is to produce materials which combine flexibility (incorporating good drape and handling properties), and strength, embracing durability and other resistance to damage. In order to achieve flexibility and strength, fibres are used which are fine units of matter with great inherent flexibility. In traditional textile processing the fibres are arranged into yarns in which the fibres have freedom of movement so that there is flexibility under low loads. On the other hand, under high loads, the fibres pull together and lock so that high strength is achieved. Subsequently, these yarns are formed into woven or knitted fabrics and in these structures again flexibility is enhanced; but under load the yarns pull together and give high strength. Traditional textile technology has developed these particular arrangements of fibre, yarn and fabric, but clearly many intermediate processes are required and so many variables are involved.

The term nonwoven is applied to weblike assemblies of textile fibres where fibre-to-fibre bonding replaces twisting and interlocking as a means of developing strength and recoverable extensibility. The range of materials embraced by this term includes structures which are stiff, dense, two-dimensional and paperlike as well as materials which are thick, highly extensible, and highly porous. Clearly the behaviour of such assemblies will be determined by a complex interaction between fibre properties and bond characteristics[25]. In some cases the behaviour of the bond will dominate the character of the non-woven; in other cases the fibres, their geometry and mechanical properties, will contribute directly to every property of the fabric. In contrast woven and knitted fabrics are much more complicated since the fibres are not homogeniously distributed throughout the fabric. Thus most fabric properties are influenced more by the yarn and fabric structural parameters than the fibre properties. These structural parameters are very difficult if not impossible to control accurately, and consequently they cannot be assumed to be constant throughout a series of experimental fabrics. Therefore, it should be possible to control more accurately the variables involved in the production of needle-felted fabrics and so these materials were used for the experimental work.

CHAPTER TWO

REVIEW OF LITERATURE

2.1. Studies On The Theories Of Sound Absorption

The theory of sound absorption was developed at least partially long ago by Stokes[26] and Kirchhoff[27]. Owing to its great importance for practical purposes the absorption of sound by porous walls initially was studied by Rayleigh[23] and Crandall[28], who assumed porous material to have a rigid solid continuous frame containing a number of parallel cylindrical pores open at the surface of the material and normal to this surface. According to them, dissipation of sound energy can be postulated to take place in such a porous material by the following mechanisms:

(a) viscous losses in the boundary layer of the walls of each capillary tube owing to relative motion between the contained viscous, conducting and compressible fluid and the solid walls; and

(b) heat conduction, that is exchange of heat energy between the contained fluid and capillary walls during cycles of fluid compression and rarefaction.

Much work was done in the field of sound absorption between 1930 and 1950, and most of this work expressed the sound absorbing properties of a fabric in terms of its sound absorption coefficent and acoustic impedence.

The sound absorption coefficient of a material is defined[29] as the ratio of the intensity of the sound absorbed by the material to the intensity of sound incident upon it. It has been demonstrated in a number of ways[30-34] that the absorption coefficient entering into acoustical formulae is not a fundamental property and considerable disagreement in experimental results[35] was found to exist not only amongst the various methods employed but also amongst different observers using the same method. It was noticed that the measured value of the absorption coefficient changed when the material was placed in different rooms[35-37] and for some materials it changed with the angle of incidence of the sound wave[38]. This led to an increasing tendency[39-41] to consider the acoustic impedence of the wall material (defined[42] as the complex ratio between the sound pressure and the normal air velocity at the wall), as a more useful measure of the absorbing property of the wall material than the absorption coefficient.

There are several papers by Zwikker, Kosten and Eijk(43-45), Scot(46), Morse and Bolt(47) and Morse, Bolt and Brown(48) on the acoustic impedence of materials. Each of these studies approached the subject differently and analysed different phases of the subject. The result was that divergent views arose.

Zwikker et. al.(43-45) have made it clear that the acoustic behaviour of a porous material can be described completely with the aid of three characteristic constants of the material, namely, the cavity factor, the specific resistance to a current of air, and the structure factor. The latter quantity can not be assigned an accurate value, arising from the fact that the pores in the material do not lie exactly in the direction of propagation of sound. Their theoretical analysis is well conceived and the derivation of the theoretical equations allows for all values of stiffness of materials whose porosity is nearly unity. However experimental verification of the theory is not completely convincing, since experiments were not performed on specially selected samples of porous materials but on specimens of sound absorbing structures, made from drinking straws and from small glass tubes. Nevertheless these results are in complete accordance with the three constant theory. Kosten(49) stated that the value of the structure factor is generally greater than three. However Kosten and Zwikker(50) pointed out that it is hardly possible to calculate the structure factor in advance simply from a description of the sample.

Scott(46) discussed recent theories relating to the wave propagation of acoustic disturbances in homogeneous, isotropic porous media, and gave a treatment of the propagation of an acoustic disturbance in three dimensions in such a media following the lines of Wintergerst(51), Mona(52) and Morse and Bolt(53), theoretical analysis was based on the assumption that the effect of the fibres could be regarded as modifying the inertia and compressibility of the air. The general theory is expressed in terms of two complex parameters which respectively take the place of the wave-length constant and the mean density of the air. His theory shows that numerical values of the components of the complex parameters can be obtained experimentally at a given frequency by measurement of the velocity of propagation of sound in the medium. Calculations of inertia, resistance and compressibility made from the measured complex parameters suggest frequency dependence of these parameters.

In much of the literature mentioned above, attention was directed towards deriving formulae for the calculation of the sound absorption coefficent and of the normal specific acoustic impedence of materials. Such formulae are not in themselves of direct value in the determination of the attenuating properties of materials when used as in the case of a speaker cover. For the case of homogeneous, isotropic materials, the more basic quantities desired are the propagation constant with its real and imaginary parts, namely the attenuating constant and the phase constant respectively. The attenuating constant is a property of the material itself and is not dependent on the mounting conditions; nor is its use restricted to formulae for absorption or attenuation alone.

2.2. Acoustic Studies Of Textile Products

Problems arising from an increase in the ambient background noise and the trend towards modern building designs have necessitated the use of noise attenuating materials. Many of these materials developed especially for multiple units are as strong as conventional building materials but are lighter and provide inferior sound insulation than traditional constructions. Also in todays buildings, extensive use is made of glass and other hard reflective surfaces which increase reflection of noise within the room and consequently increase the annoyance. In situations such as these, textile materials[54] have an important role to play in the living and working environment. Since materials of this type form an integral part of many acoustic designs, the important acoustic properties must be determined, that is, a scientific measure of their effectiveness as 'noise controllers' must be effected. Recently, measurement of sound absorption by textile products has been carried out to a limited extent. Studies, using various methods, have revealed the influence of construction variables on the reduction in airborne sound by carpets, draperies, and general fabrics.

Early studies on the acoustical properties of carpets were carried out by Harris(55). He measured the normal absorption coeficient of several hundred carpet samples by the tube method and related it to the backing material, pile structure, fibre content, yarn weight, density, pile height and difference in underlays. It was found that a latex coating on the back of a carpet, which increased impermeability and flow resistance, resulted in increased low frequency absorption and decreased high frequency absorption. The pile structure, fibre content and yarn weight were not shown to be significant variables, whereas the pile height and pile thickness had an appreciable effect on absorption. Other studies similarly showed a direct relationship between the pile height(54), pile density(54,57), and the pile weight(58) of carpets and sound absorption.

Nute and Slater(59) investigated the dependence of sound transmission loss on carpet pile parameters in a laboratory sound tube at five different frequencies. Their tests indicate that the pile thickness and the weight have only a minor influence on sound transmission loss and that the pile density had virtually no effect. They postulated that other factors that affect the total air permeability of the material may be more important. They also showed that the percentage of sound absorbed within a chamber is proportional to the size of the sample used.

Nanson and Slater(60) investigated the influence of the pile parameters on echo-loss absorption by carpets using a sweep frequency technique(61). They found that the pile parameters are not significant in determining the acoustic behaviour of a carpet.

Aso and Kinoshita(62-64) analysed the mechanism of the absorption of the sound wave by measuring the normal incident absorption coefficient of fabrics of different densities by the tube method. Their studies show that there are two types of mechanisms of sound wave absorption by fabrics. One is the "viscosity resistance type" in which absorption occurs because a sound wave, in passing through the fabric, produces an energy-loss to overcome the frictional resistance between the fibres and the air in it. The other, the "resonance type" occurs because the sound wave vibrates the entire system composed of the fabric and the elastic air space behind the fabric.

Only a few papers have been published on the transmission properties of textile fabrics. Perhaps the most important of these are by Slater(65) and Nute and Slater(66). They measured the transmission loss of fabrics and investigated the effect of fabric weight, cover and thickness. For all three of these parameters they obtained rather "poor correlation" with sound absorption.

In conclusion it must be stated that literature specifically relating to sound-absorbing materials develops theories which are essentially macroscopic, and these do not allow adequately for the microstructure of the porous media. Moreover, much of the published work appeared to be deficient in terms of realistic discussion and comparison between experimental and theoretical results.

Initial work carried out in the School of Textiles(67), Leicester Polytechnic, on needle-felted fabrics suggested that the sound absorbed by such fabrics was influenced considerably by the fabric and fibre properties. Moreover, absorption was found to increase with fabric mass per unit area and fabric density.

2.3. Studies On Measurement Of Sound Absorption

A number of methods are available for the measurement of sound absorption(68). The best known is the reverberation method(69-73). This method admits a sound wave into the sample in a chamber from random directions and uses the data obtained from the rate of decay of the sound wave in the chamber, to determine the reverberation sound absorption coefficient of a sample within the chamber.

Another widely used method is the impedence tube technique[74-80] in which sound waves are admitted only vertically into the sample and in which the acoustic impedence is determined, on the basis of standing wave measurements. By suitable calculation, the absorption coefficient can be determined if required, from the acoustic impedence data.

The use of an acoustic tube for measuring the absorption coefficient of small samples of acoustical materials first was proposed by Taylor[74] in 1913. In 1928 Wente and Bedell[75] of the Bell Telephone Laboratories, prepared a paper outlining three methods of determining acoustic impedence and absorption coefficient by the tube method. They also describe an acoustic tube which had been built and the results they obtained in the measurement of various types of acoustical material.

Roger and Watson[76] have pointed out as mentioned earlier that the reverberation chamber and the impedence tube methods often lead to different values of sound absorption coefficient. Even measurements of the same sample by different observers in different reverberation chambers lead to a wide distribution of values [78]. Further, the theoretical argument used in converting acoustic impedence values to sound absorption coefficient are open to criticism[79]. They have described a pulse method for the determination of the absorption coefficient using a sound mirror to produce directed sound pulses. This allows the determination of the coefficient by essentially a free field method. They concluded that the pulse method is useful in determining the variation of absorption coefficient as a function of the angle of incidence at relatively high frequency. This method has the advantage that measurements may be carried out in an ordinary laboratory space.

Nute and Slater[61] have described a new swept-frequency technique for studying the acoustic behaviour of materials. This method has certain advantages over the established methods where a rapid inexpensive assessment of the approximate acoustic performance of a material is required in the laboratory or in field situations. Their method used a constant sound power output and involved measurements of the resulting sound pressure level in a room, in the presence and absence, respectively, of the absorbing material. A band of noise was used as the source and, by calculating the room absorption, an estimate of the sound absorption coefficient of the specimen was obtained.

CHAPTER THREE

THEORY OF SOUND ABSORPTION BY POROUS FABRICS

3.1. Introduction

Of all the literature surveyed, none considers the dissipation of sound energy in terms of transmission loss resulting from placing a fabric in the sound path and thus evaluating the effect of changing basic fabric and fibre parameters. It is the intention of this chapter to determine from first principles what fraction of a sound wave is absorbed or converted into a form unavailable to the acoustic field so making it possible to derive the characteristics required for the most efficient absorbent, particularly from the standpoint of their manufacture. The expression derived in this chapter then will be compared with the experimental results to see if there are any discrepancies.

Consider the energy consumption of a sound wave by a fabric in a sound field. Sound is dissipated in a fluid-saturated porous solid according to the restrictions on the movement of the fluid within it. A convenient model microstructure for such a material is one of a rigid solid matrix through which run cylindrical capillary pores with constant radius normal to its surface. This type of model enables the use of Kirchoffs theory for propagation in narrow tubes with rigid walls. The mechanisms of energy dissipation, therefore, may be identified as:

(a) viscous loss in the boundary layer at the walls of each capillary tube associated with the relative motion between the contained (viscous) fluid and the solid walls; and,

(b) heat conduction between the compression and rarefactions of the contained (compressible) fluid and the conducting solid walls.

On the basis of these mechanisms, relationships between the acoustic and the physical properties of the fibre block will be derived.

3.2. Fabric Model and Assumptions

3.2.1. Fabric Model

A needled fabric derives its strength from the interfibre friction and fibre entanglement. The web before needling has the fibres oriented in isolated layers composing the web. The fibres on the surface remain on the surface over their whole length so that they never develop an appreciable tension and do not press on the layer below, which, in its turn, also is unable therefore to develop tension. The diiferent layers of the web being isolated from each other, provide no integrity to the structure. This structure is very delicate and its strength therefore is expected to be low as the fibres can slip over each other easily. When the web is needled, the fibres are reoriented in the third dimension so that they migrate from the surface to the inside of the web and back again in a continous form. The punching action also pushes the fibres into closely packed bunches providing compactness to the web and a high frictional resistance to the withdrawal of fibres. The fibre migration caused by needling plays an important role in giving cohesion to the needled structure.

Due to the needled structure being rather complicated to deal with in an exact quantitative manner, an idealised model of the fabric structure has been suggested which is much simpler than reality. In this simplification, all the fibres in the structure are assumed to have the same migration pattern throughout the body of the fabric and to lie normal to the surface of the fabric, with sufficient crossing over each other to develop transverse pressure. The pattern of the fibre interlocking is assumed to follow regular geometric path which provides symmetry of the whole fibre assembly about the fabric axis. The pattern of migration of the whole fibre assembly is considered symmetrical about the fabric axis such that the fibres lie almost perpendicular to the length of the fabric creating capillary pores normal to the surface through which fluid can be transmitted. In reality these pores in general will have very irregular cross sections, but for the idealised model structure these are assumed to be regular.

3.2.2. Assumptions

1 a) If there are c cm^3 of solid material per unit volume of the needle-felted fabric, then the fraction of the space available for the movement of fluid per unit volume of the fabric medium is (1-c) cm^3.

1 b) If there are S_1 cm^2 of open space per A cm^2 of medium and S_2 cm^2 of solid material per A cm^2 of medium. Then:

$$S_1 + S_2 = A$$

or, for an element of distance Δx

$$\underset{\text{(volume of air)}}{S_1 \cdot \Delta x} + \underset{\text{(volume of solid)}}{S_2 \cdot \Delta x} = \underset{\text{(total volume)}}{A \cdot \Delta x}$$

Therefore $(1-c) \cdot A \cdot \Delta x + c\, A \cdot \Delta x = A \cdot \Delta x$

2) The fabric is acoustically homogeneous and its porosity and fibre arrangement are uniform.

3) The compressibility of the fibre material is negligible since it is small compared with that of the air.

4) Only first order approximations are considered.

5) Dissipation of sound energy due to scattering of sound by the fibre is neglected.

6) The wavelength of the sound wave is large compared with the fibre size.

3.3. Theory of Sound Transmission Loss

3.3.1. Introduction

Consider a homogeneous isotropic medium placed in the path of a sound wave, whose pressure p(x) depends upon the time t and on distance x according to the relationship:

$$p(x,t) = A_1 \exp\left[jw \cdot \left(t - \frac{x}{C}\right)\right]$$

where A_1 is the peak pressure, $w = 2\pi \cdot$ frequency, $j^2 = -1$ and C the velocity of propagation of sound. The presence of the medium in the sound path will result in energy loss (sound absorption). If the wave amplitude decays (as a result of energy loss) with distance by a factor $e^{-\alpha x}$ then the sound pressure will depend upon the time and the distance in accord with the following general equation for a damped sine wave:

$$p(x,t) = \left\{ A_1 \exp(jw(t - \frac{x}{C})) \right\} \exp(-\alpha x)$$

$$\text{or } p(x,t) = A_1 \exp(jw(t - \frac{x}{C}) - \alpha x) \qquad \text{.........(3.1)}$$

At the site x=0, the wave pressure is:

$$p(0,t) = A_1 \exp(jw \cdot t) = p_o \qquad \text{.........(3.2)}$$

putting $\frac{w}{c} = \beta$ and if $\gamma = \alpha + j\beta$, then for the damped sine equation the shorter analytical form is obtained, that is:

$$p(x,t) = p_o \exp(-\gamma x) \qquad \text{.........(3.3)}$$

The constant γ, is called the propagation constant of the medium, its real part α is called the attenuation constant and its imaginary part β the phase constant. The real part α characterises the exponential loss of amplitude of the wave in the direction of propagation.

In analogy with other fields, in acoustics, a logrithmic measure of energy or power ratio often is used. For example if I_1 and I_2 are two sound intensities at two points in a porous material then the difference in level is given by:

$$\Delta L = 10 \log(\frac{I_1}{I_2}) \text{ dB} \qquad \text{............(3.4)}$$

But in simple sound fields the sound intensity is proportional to the square of the sound pressure. Thus the difference in level can be expressed in terms of the root mean square value of P_1 and P_2 of the sound pressure that corresponds to the intensities I_1 and I_2. Thus:

$$\Delta L = 20 \log(\frac{P_1}{P_2}) \text{ dB} \qquad \text{...........(3.5)}$$

Since the sound pressure in the direction of propagation decreases as $e^{-\alpha x}$, the difference in sound level between two points seperated by a distance Δx (fig 3.1) thus is given by:

$$\Delta L = 20 \log \frac{P_o \exp(-\alpha(x + \Delta x))}{P_o \exp(-\alpha x)}$$

$$= - 8 \cdot 69 \cdot \alpha \cdot \Delta x \qquad \text{..........(3.6)}$$

Hence the decrease in sound level as a result of a particular fabric being present in the sound path may be

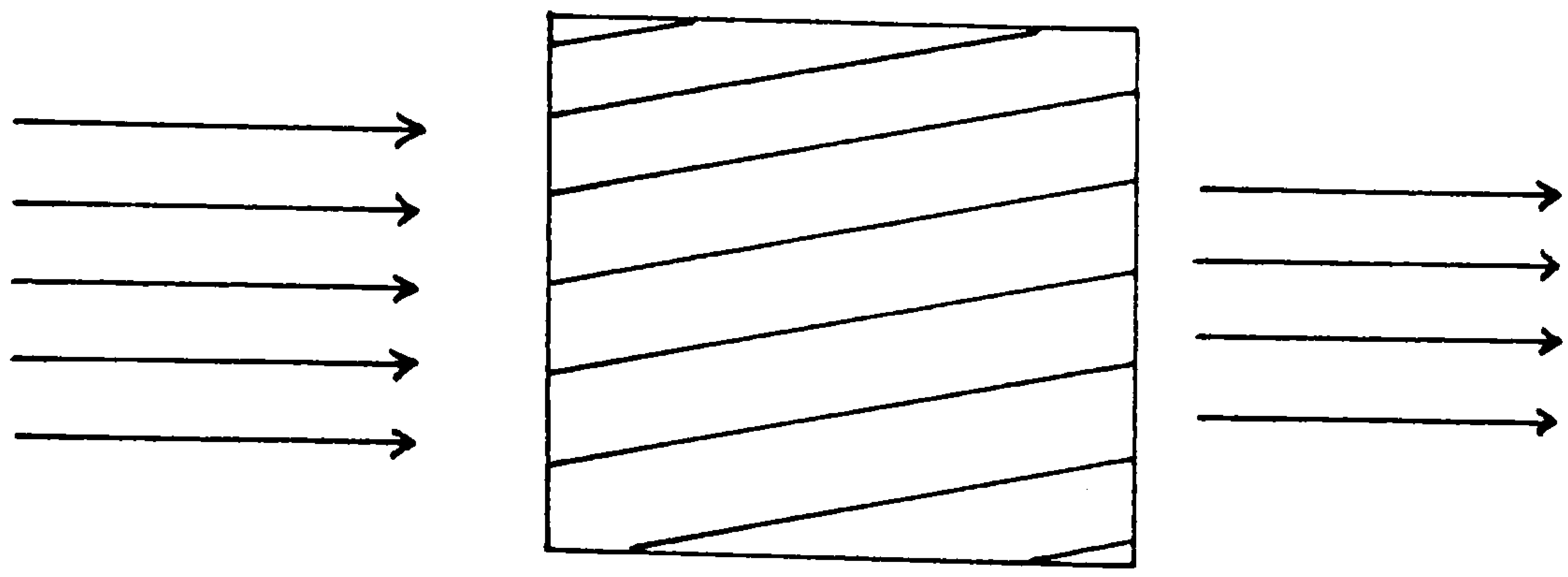


Figure 3.1. Sketch showing the decrease in sound pressure, of a sound wave propagating in a sound absorbing material

determined by substituting the value of α and Δx for that fabric in equation 3.6. Thus α and Δx fully determine the attenuating properties of the material.

The theoretical deduction for α for any medium can be accomplished by obtaining a solution of the form:(81)

$$p(x,t) = A_1 \exp(jw(t - \frac{x}{C}) - \alpha x) \qquad \text{.........(3.7)}$$

to the general wave equation:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{(\text{constant})} \frac{\partial^2 p}{\partial t^2} \qquad \text{.........(3.8)}$$

propagating in the air filled pores of the porous material. The general sound wave can be obtained by solving simultaneously the equations of continuity, state and motion which describe the changes of particle velocity, density of the medium and sound pressure.

With the help of the above fabric model and adopting the assumptions proposed, the equations of continuity, state and motion now can be derived. Subsequently these will be solved simultaneously to find the general sound wave equation.

3.3.2. Equation Of Continuity

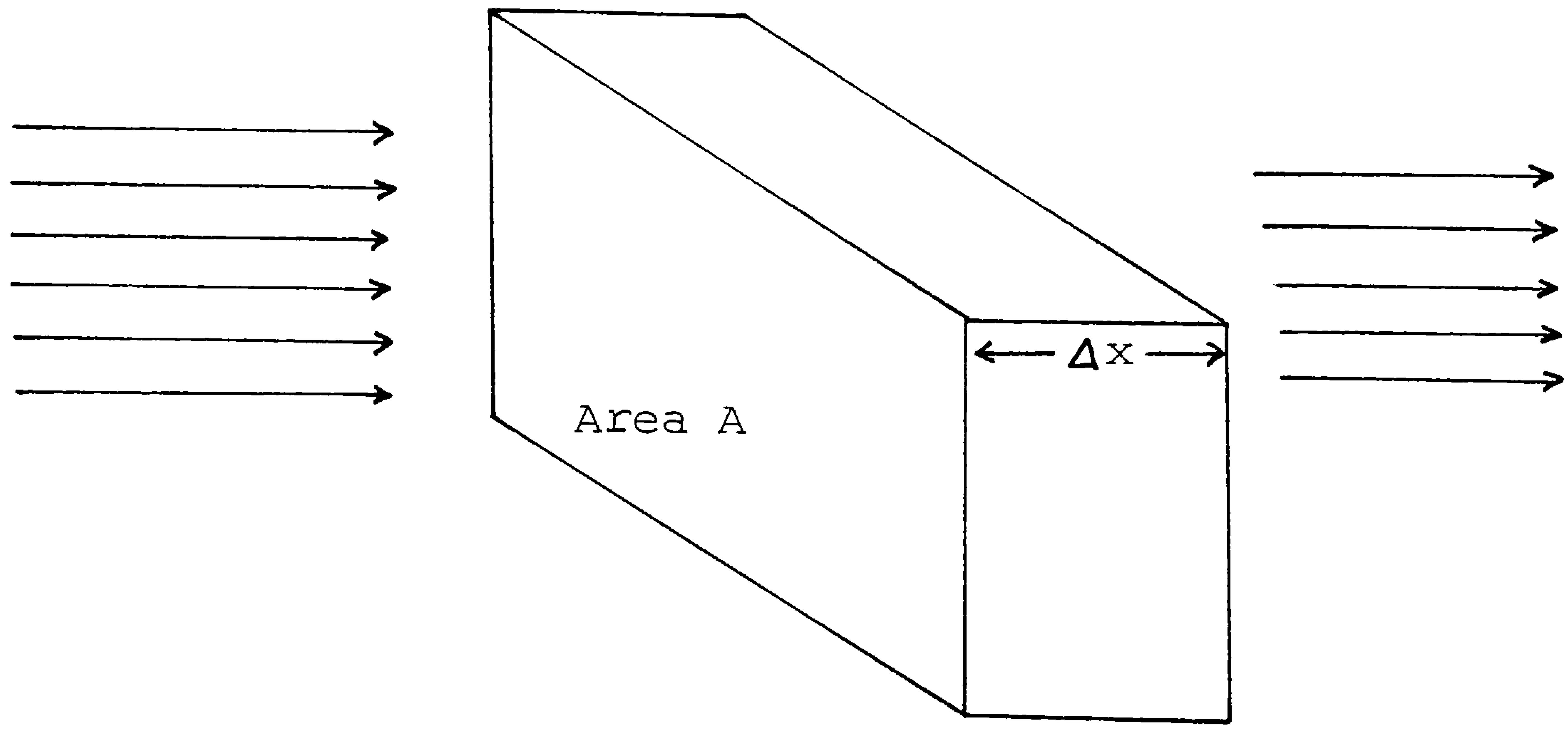


Figure 3.2 Motion of compressible fluid through an parallelepiped

Consider the motion of a fluid having no sources or sinks, that is, there are no points at which fluid is produced or disappears, (the concept of the fluid state includes gases), through a small rectangular parallelepiped shown in figure 3.2, which has volume:

$$\Delta V = A \cdot \Delta x$$

Since there are c cm^3 of solid material per unit volume of medium. Therefore there are $(c \cdot \Delta V)$ cm^3 of solid material in the parallelepiped, and:

$$\Delta V - c \cdot \Delta V = \Delta V(1-c)$$

is the fraction of space open to the fluid.

Let ρ_o represent the average density of the air in the volume ΔV and let V_S represent the average velocity of the fluid particles entering through one of the faces of area A as in figure 3.2. It is assumed that the fluid is compressible, that is, the fluid density (ρ) depends on the position in the parallelepiped and may also depend on time (this is a valid assumption in the case of gases because of their considerable compressibility).

Consider the change in mass included in the parallelepiped by considering the flux across the boundary, that is, the total mass leaving the parallelepiped per unit time. This can be done by considering the flow through the left hand face of area A. The mass of fluid entering through that face during a short interval Δt is given approximately by:

$$\rho_o V_S \, A \Delta t$$

The mass of fluid leaving through the opposite face during the same interval is given approximately by:

$$\left[\rho_o V_S + \frac{\partial}{\partial x}(\rho_o V_S) \, \Delta x \right] A \Delta t$$

The difference between the two equations gives the total accumulation of mass in the parallelepiped. This accumulation of mass is caused by the time rate of change of the density and is thus equal to:

$$\left(-\frac{\partial \rho}{\partial t} \Delta t\right) \Delta V \, (1-c)$$

Equating the two equations:

$$\frac{\partial}{\partial x}(\rho_o V_S) \Delta x \cdot A \cdot \Delta t = -\frac{\partial \rho}{\partial t} \Delta t \, (1-c) \Delta V$$

$$= -\frac{\partial \rho}{\partial t} \Delta t \, (1-c) \, A \Delta x$$

If the porosity (h) of the parallelepiped is defined as:

$$h = \frac{\text{Volume of open space in the parallelepiped}}{\text{Total volume of the parallelepiped}}$$

$$= \frac{(1-c)\Delta V}{\Delta V}$$

$$= (1-c) \qquad \text{..........(3.9)}$$

Thus:

$$\rho_o \frac{\partial V_S}{\partial x} = -h \frac{\partial \rho}{\partial t} \qquad \text{..........(3.10)}$$

This is the equation of continuity for a compressible fluid flowing through the parallelepiped.

3.3.3. Equation of State

3.3.3. a) Introduction

The functional relation between pressure, volume (density), and temperature of a body is termed the equation of state, and is one of the most important relationship describing its thermal properties. The fabric (needle-felted) employed in this project can be treated as a mixture of fibres and air. It is characterised by large (above 95%) porosity and is made of fine fibres. When a sound wave train is propagated in such a fabric, the compression (or dialation) occurs mainly in the air fraction of the fabric, resulting in a temperature rise (due to compression) or fall (due to dialation) in the fabric. The heat flow developed as a result of the temperature difference between the fibres and air causes a phase lag between the pressure wave and the density wave giving rise to absorption in the medium. The effect of compression must depend on the rapidity of the alternations (frequency). Below a certain limit of frequency, the heat in excess, or deficit, would have time to adjust itself, and the temperature would remain sensibly constant. In this case, the relationship between pressure and density would be the standard relationship. On the other hand, above a certain limit of frequency, the gas would behave as if confined in a non conducting vessel (isothermal case). Now although the circumstances of the actual problem are better represented by the latter than the former supposition, there may be a sensible deviation from the laws of pressure and density involved earlier. By taking into consideration the thermal equation as a result of the temperation variation and the compression equation a relationship now will be derived between pressure and density (equation of state).

3.3.3. b) Thermal Equation

Considering the heat developed as a result of compression, a relevant question is whether a small part of the heat escapes by conduction before producing its full effect. Consider a cylindrical volume v in the fibre block of large dimensions compared with the radius of the fibre and the distance of separation, as shown in figure 3.3 If

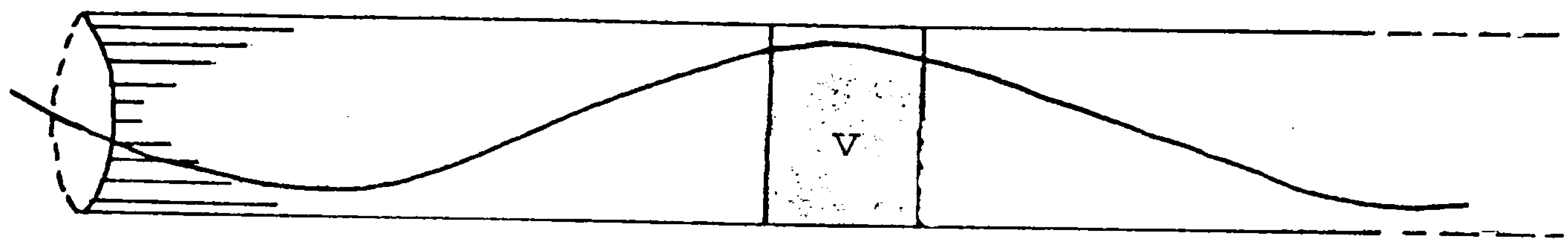


Figure 3.3 Assumed pore in the porous material

sound waves are travelling in the volume under consideration, at any point the sound pressure, the three components of the vector velocity, and the excess temperature may be defined. All are functions of position in the volume and the time. In general the thermal capacity of a porous material in a unit volume is very much greater than the thermal capacity of the contained gas. Owing to the thermal conductivity of the air, the heat generated tends to flow to the boundary of the volume under consideration, resulting in a temperature variation along the radius of the volume. This temperature variation will be zero at the boundary.

It is assumed that the pressure is constant in the whole volume under consideration (this is justified by the fact that the radius of the cylindrical volume under consideration is extremely small compared to the wavelength of the sound wave). The variation of pressure in the axial direction may be simplified since $\frac{\partial p}{\partial x}$ can be made zero by compressing the layer of air under consideration from either sides exactly symmetrically, viz, by equal and opposite displacement of the flat terminal surfaces of the layer. In terms of wave motion, a thin layer of air is taken out of a standing wave at the position where the pressure is maximum (figure 3.3) than clearly $\frac{\partial p}{\partial x}$ will be zero.

Equations for the temperature variation along the radius of the volume now can be derived using the above assumptions by considering a body which is insulated so that no heat is lost to the surroundings. Consider the flow of heat before steady conditions are reached when heat is supplied to one face. The analysis of heat flow by conduction through a material involves the determination of the temperature distribution. In general terms the distribution is described by a partial differential equation and the theoretical analysis of the heat flow depends upon the possibility of solution of this equation. The general equation for one-dimensional heat conduction through a plane wall in the z direction (figure 3.4a) is given by:[82]

$$Q = -K'A\frac{T_2 - T_1}{dz} \qquad \text{.........(3.11)}$$

where Q is the rate of flow of heat, A is the area of the wall, T is the temperature and K' is the thermal conductivity.

The general equation in radial coordinates may be found by an energy balance on an annular ring as shown in figure 3.4b and as discussed by Cornwel[83]. For simplicity it is assumed that there is complete symmetry about the z axis. Equating the difference between the heat flow rates into and out of the cylinder to the rate of change of internal energy (U_i) with time (t) yields:

$$Q_r + Q_z - (Q_{r+dr} + Q_{z+dz}) = \frac{\partial U_i}{\partial t}$$

and the respective terms are given by:

$$Q_r = -2\pi r\,dz\,K'\frac{\partial T}{\partial r}$$

$$Q_z = -2\pi r\,dr\,K'\frac{\partial T}{\partial z}$$

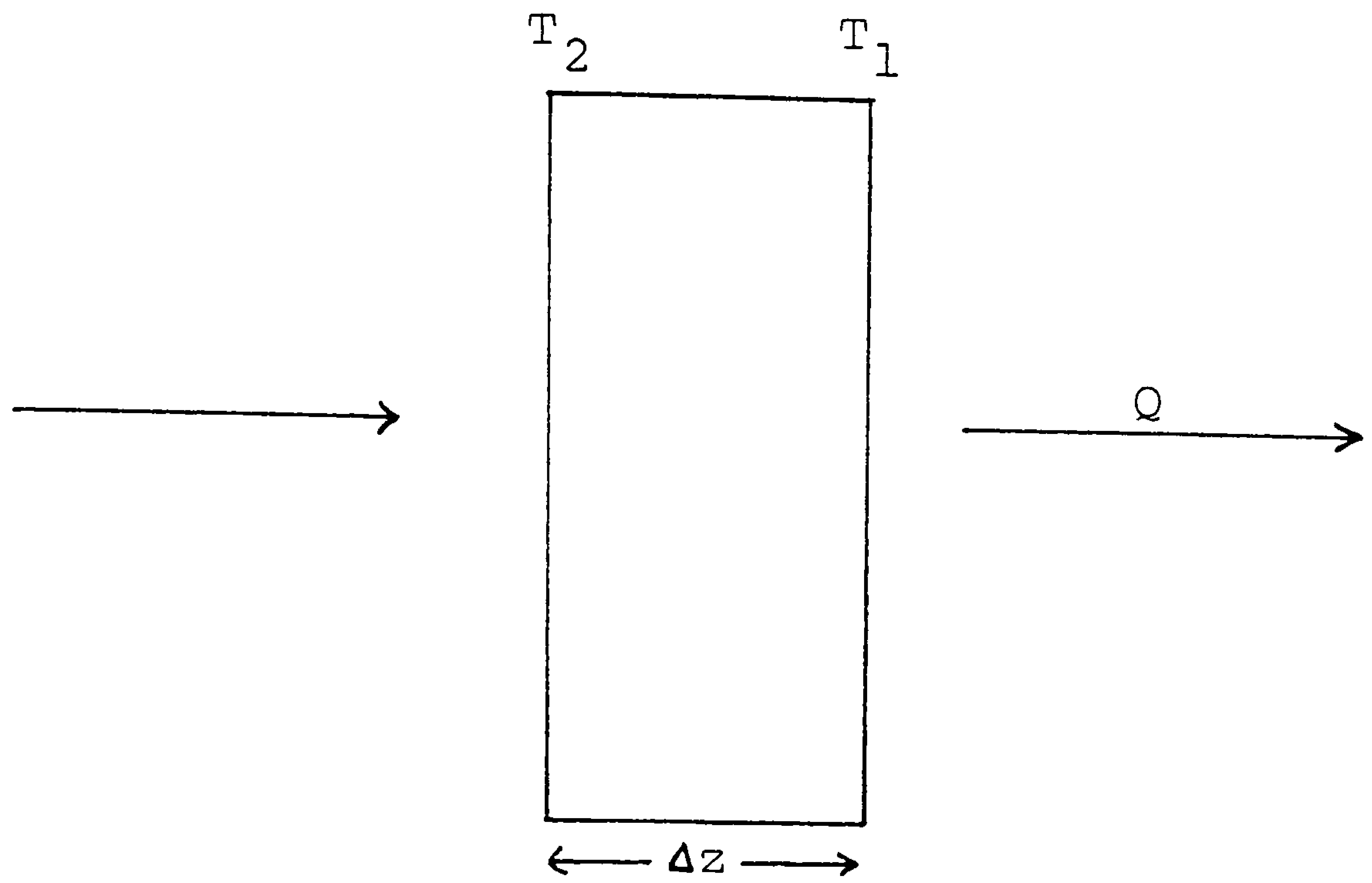
$$Q_{r+dr} = -2\pi r(r+dr)\,dz\left[K'\frac{\partial T}{\partial r} + \frac{\partial}{\partial r}\left(K'\frac{\partial T}{\partial r}\right)dr\right]$$

$$Q_{z+dz} = -2\pi r\,dr\left[K'\frac{\partial T}{\partial z} + \frac{\partial}{\partial z}\left(K'\frac{\partial T}{\partial z}\right)dz\right]$$

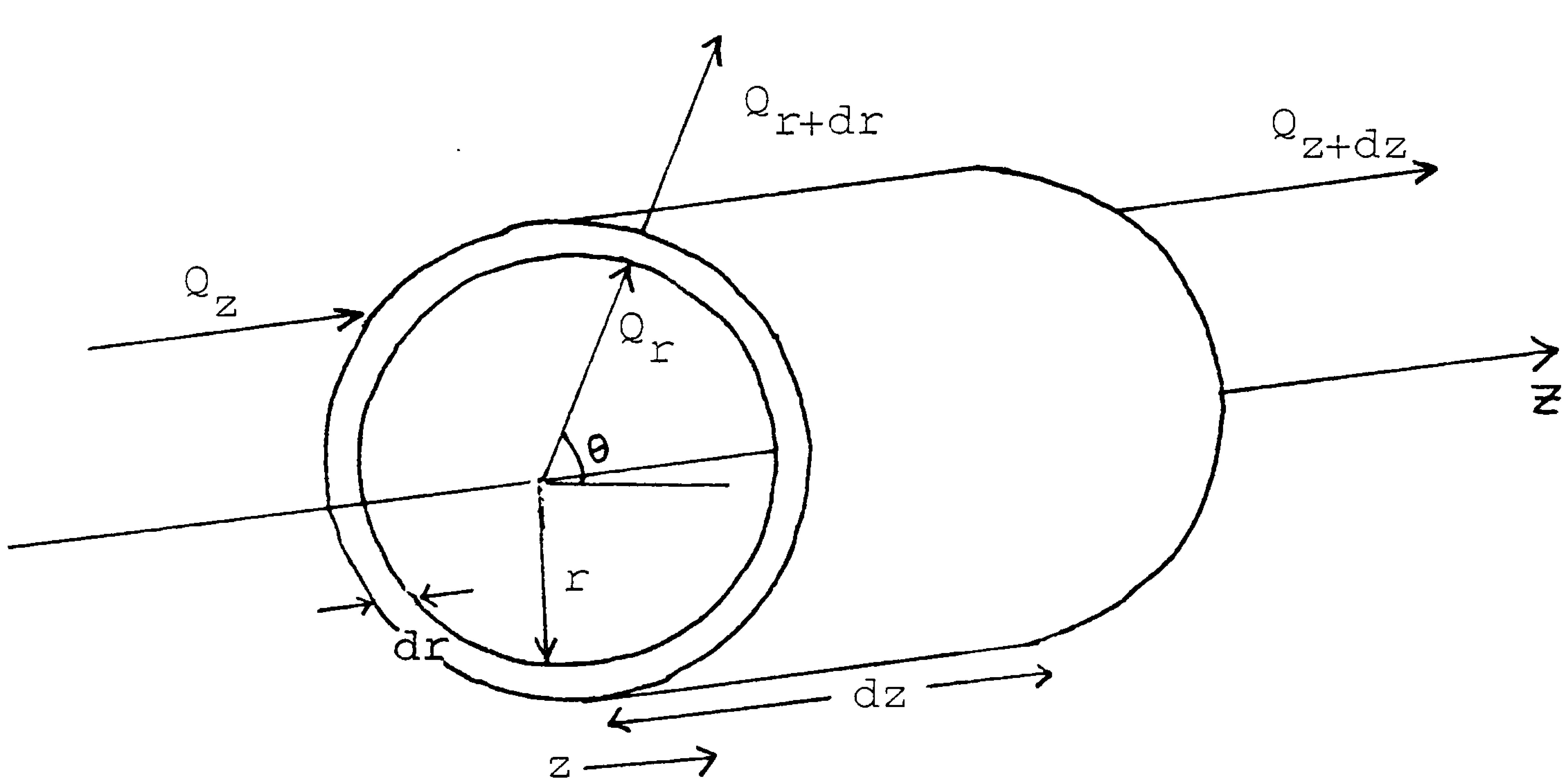
$$\frac{\partial U_i}{\partial t} = \rho C_s 2\pi r\,dr\,dz\frac{\partial T}{\partial t}$$

where ρ and C_s are the density and specific heat respectively. Substituting, neglecting second-order differentials, yields:[23,84,85]

$$\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\frac{\partial\theta}{\partial r} + \frac{\partial^2\theta}{\partial z^2} = \frac{\rho C_p}{K'}\frac{\partial\theta}{\partial t}$$



<u>Figure 3.4a</u> Conduction of heat through a plane wall



<u>Figure 3.4b</u> Conduction of heat through an annular element

where θ is equal to the ratio of excess temperature (δT) to the equilibrium temperature (T_o). For no variation in the z direction, this reduces to:

$$\frac{\partial \theta}{\partial t} = D\left[\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r}\right]$$

where D is the thermal diffusity defined as:

$$D = \frac{K'}{\rho C_s}$$

Also for adiabatic compression:[86]

$$T = \rho^{(k-1)}.\text{constant} \qquad \text{.........(3.13)}$$

where k is the ratio of specific heat at constant pressure (c_p) to the specific heat at constant volume (c_v). The above equation can be rewritten as:

$$\log(T) - (k-1)\log(\rho) = \text{constant}$$

Differentiating:

$$\frac{\partial T}{T_o} - (k-1)\frac{\partial \rho}{\rho_o} = 0$$

and introducing:

$$\theta = \frac{\partial T}{T_o} \qquad \text{and} \qquad S = \frac{\partial \rho}{\rho_o}$$

where S is equal to the ratio of the increment of density ($\partial\rho$) to the original density (ρ_o), gives:

$$\theta = (k-1)\cdot S$$

The variation of θ with time is therefore given by:

$$\frac{\partial \theta}{\partial t} = (k-1)\frac{\partial S}{\partial t} \qquad \text{..........(3.14)}$$

the full thermal equation thus becomes:

$$\frac{\partial \theta}{\partial t} = (k-1)\frac{\partial S}{\partial t} + D\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial t}\right) \qquad \text{.........(3.15)}$$

This equation expresses the fact that the temperature can rise by compression as well as by heat conduction.

3.3.3. c) Compression Equation

In a perfect gas:

$$P\,V = RT \qquad \text{or} \qquad P = R\rho T$$

where P is equal to the pressure, V is equal to the volume, T is equal to the temperature, R is equal to the gas constant, and ρ is equal to the density. The above equation can be rewritten as:

$$\log(P) - \log(\rho) - \log(T) = \text{constant}$$

Differentiating:

$$\frac{\partial P}{P} - \frac{\partial \rho}{\rho} - \frac{\partial T}{T} = 0$$

and introducing p and p_0 as the excess (∂p) and equilibrium pressure (p). The equation therefore becomes:

$$p = p_0 (S + \theta) \qquad \text{.........(3.16)}$$

3.3.3. d) Equation of State

The dependence on time of all quantities in the thermal equation (3.15) and the compression equation (3.16) can be assumed to vary as exp(jwt) so that $\frac{\partial}{\partial t}$ can be replaced by jw (as shown below):

> If $p(t) = \exp(jwt)$
>
> $$\frac{\partial p(t)}{\partial t} = jw \exp(jwt)$$
>
> $$= jw\, p(t)$$
>
> Hence $\frac{\partial}{\partial t}$ can be replaced by jw.

The thermal equation:

$$\frac{\partial \theta}{\partial t} = (k-1)\frac{\partial S}{\partial t} + D\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r}\right)$$

thus becomes:

$$jw\theta = (k-1)\, jwS + D\left(\frac{\partial^2 \theta}{\partial r} + \frac{1}{r}\frac{\partial \theta}{\partial r}\right)$$

and replacing $\frac{\partial^2 \theta}{\partial r^2}$ by θ'' and $\frac{\partial \theta}{\partial r}$ by θ', gives:

$$jw\theta = (k-1)\, jwS + D\left(\theta'' + \frac{\theta'}{r}\right)$$

or:

$$S = \frac{1}{jw(k-1)}\left[jw\theta - D\theta'' - \frac{D}{r}\theta' \right] \qquad \text{.........(3.17)}$$

$$= \frac{D}{jw(k-1)}\left[\frac{jw\theta}{D} - \theta'' - \frac{\theta'}{r} \right]$$

Substituting for S in the compression equation (3.16) and rearranging, as below, gives:

$$\frac{p}{p_o} = \theta + \frac{D}{jw(k-1)}\left[\frac{jw\theta}{D} - \theta'' - \frac{\theta'}{r}\right]$$

or, $$\frac{jw(k-1)}{D}\frac{p}{p_o} = \frac{jw(k-1)}{D}\theta - \frac{jw\theta}{D} - \theta'' - \frac{\theta'}{r}$$

or, $$\frac{jw(k-1)}{D}\frac{p}{p_o} - \frac{\theta jw}{D}(k-1+1) + \theta'' + \frac{\theta'}{r} = 0$$

Therefore: $$\theta'' + \frac{\theta'}{r} - \frac{jwk}{D}\theta + \frac{p}{p_o}\frac{jw(k-1)}{D} = 0 \quad \ldots(3.18)$$

Following the standard methods listed in most mathematical text books[87,88], the general solution for the above equation is found by finding the particular integral and the complementary function of the equation:

$$\begin{pmatrix}\text{general}\\ \text{solution}\end{pmatrix} = \begin{pmatrix}\text{particular}\\ \text{integral}\end{pmatrix} + \begin{pmatrix}\text{complementary}\\ \text{function}\end{pmatrix}$$

To find the complementary function put:

$$\theta'' + \frac{\theta'}{r} - \frac{jwk}{D}\theta = 0 \quad \ldots\ldots\ldots\ldots(3.19)$$

also it can be assumed that θ may be represented by an infinite power series of the form:

$$\theta = r^m(a_o + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + \ldots\ldots\ldots)$$

where m may be any (real or complex) number and a_o, a_1, .. are constants. Multiplying both sides by A, where:

$$A = -\frac{jwk}{D}$$

gives: $$A\theta = Ar^m(a_o + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + \ldots)$$

Differentiating with respect to r, to find the term θ':

$$\theta' = ma_o r^{(m-1)} + (m+1)a_1 r^m + (m+2)a_2 r^{(m+1)}$$
$$+ (m+3)a_3 r^{(m+2)} + (m+4)a_4 r^{(m+3)} + \ldots\ldots\ldots$$

or: $$\frac{\theta'}{r} = r^m\Big[ma_o r^{-2} + (m+1)a_1 r^{-1} + (m+2)a_2 + (m+3)a_3 r$$
$$+ (m+4)a_4 r^2 + \ldots\ldots\ldots\ldots\Big]$$

Differentiating once more with respect to r, to find the term θ'';

$$\theta'' = (m-1)ma_o r^{(m-2)} + m(m+1)a_1 r^{(m-1)} + (m+1)(m+2)a_2 r^m + (m+2)(m+3)a_3 r^{(m+1)} + (m+3)(m+4)a_4 r^{(m+2)} + \dots\dots$$

or $$\theta'' = r^m \left[(m-1)ma_o r^{-2} + m(m+1)a_1 r^{-1} + (m+1)(m+2)a_2 + (m+2)(m+3)a_3 r + (m+3)(m+4)a_4 r^2 + \dots\dots\right]$$

If the sum of the three series $A\theta$, $\frac{\theta'}{r}$, and θ'' is to vanish (as in equation 3.19), the sum of the coefficients of like powers of r must also vanish. By equating coefficients of like powers to zero, the coefficient a_o, a_1, and so on can be found, as:

(a) <u>by equating $r^{(m-2)}$</u>:

$$ma_o + (m-1)ma_0 = 0$$

or $$a_o m^2 = 0 \qquad \dots\dots\dots\dots(3.20)$$

(b) <u>by equating $r^{(m-1)}$</u>:

$$(m+1)a_1 + m(m+1)a_1 = 0$$

or $$a_1(m+1)^2 = 0 \qquad \dots\dots\dots\dots(3.21)$$

(c) <u>by equating r^m</u>:

$$Aa_o + (m+2)a_2 + (m+1)(m+2)a_2 = 0$$

or $$Aa_o + (m+2)^2 a_2 = 0 \qquad \dots\dots\dots\dots(3.22)$$

(d) <u>by equating $r^{(m+1)}$</u>:

$$Aa_1 + (m+3)a_3 + (m+2)(m+3)a_3 = 0$$

or $$Aa_1 + (m+3)^2 a_3 = 0 \qquad \dots\dots\dots\dots(3.23)$$

(e) <u>by equating $r^{(m+2)}$</u>:

$$Aa_2 + (m+4)a_4 + (m+3)(m+4)a_4 = 0$$

or $$Aa_2 + (m+4)^2 a_4 = 0 \qquad \dots\dots\dots\dots(3.24)$$

(f) and so on.

Examining the respective equations, yields:

Equation 3.20:

$$a_o m^2 = 0$$

This is the indical equation, since it serves to determine the index m. For this equation to be true either:

$$a_o = 0 \qquad \text{or} \qquad m^2 = 0$$

Equation 3.21:

$$a_1(m+1)^2 = 0$$

For this equation $a_1 = 0$, provided $m \neq -1$

Equation 3.22:

$$Aa_o + (m+2)^2 a_2 = 0$$

This can be rearranged to give:

$$a_2 = -\frac{Aa_o}{(m+2)^2}$$

Equation 3.23:

$$Aa_1 + (m+3)^2 a_3 = 0$$

This can be rearranged to give:

$$a_3 = -\frac{Aa_1}{(m+3)^2}$$

but if $a_1=0$, then $a_3=0$.

Equation 3.24:

$$Aa_2 + (m+4)^2 a_4 = 0$$

This can be rearranged and substituted to give:

$$a_4 = -\frac{Aa_2}{(m+4)^2} \qquad = \qquad \frac{A^2 a_o}{(m+2)^2\,(m+4)^2}$$

and so on.

As can be seen if $a_1=0$, then all odd terms of a will also be equal to zero, that is $a_1=a_3=a_5= \ldots\ldots=0$. Substituting for a_o, a_1, a_2, etc. in the original power series yields:

$$\theta = r^m \left[a_o + 0 - \frac{Aa_o}{(m+2)^2} r^2 + 0 + \frac{A^2 a_o}{(m+2)^2 (m+4)^2} r^4 + 0 + \ldots\ldots\ldots \right]$$

or $$\theta = a_o r^m \left[1 - \frac{(A^{\frac{1}{2}} r)^2}{(m+2)^2} + \frac{(A^{\frac{1}{2}} r)^4}{(m+2)^2 (m+4)^2} + \ldots\ldots\ldots \right]$$

Now if $a_o=0$, then $\theta=0$. Therefore m must be equal to zero, instead of a_o. The complementary function of equation 3.18 is thus:

$$\theta = a_o \left[1 - \frac{(A^{\frac{1}{2}} r)^2}{2^2} + \frac{(A^{\frac{1}{2}} r)^4}{2^2\ 4^2} + \ldots\ldots\ldots\ldots\ldots\ldots \right]$$

$$= a_o \sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}} r)^{2n}}{(n!)^2\ 2^{2n}} \qquad \ldots\ldots\ldots\ldots(3.25)$$

To find the particular integral suppose $\theta=a$, where a is an constant. Hence:

$$\frac{\partial \theta}{\partial r} = \frac{\partial^2 \theta}{\partial r^2} = 0$$

On substitution into the original equation (3.18) yields:

$$-\frac{jwk}{D} a + \frac{p}{p_o} \frac{jw(k-1)}{D} = 0$$

therefore:

$$a = \frac{p}{p_o} \frac{(k-1)}{k}$$

The particular integral therefore is:

$$\theta = \frac{p}{p_o} \frac{(k-1)}{k} \qquad \ldots\ldots\ldots\ldots(3.26)$$

The complete solution of equation 3.18. is thus:

$$\theta = a_o \sum_{n=0} \frac{(-1)^n (A^{\frac{1}{2}} r)^{2n}}{(n!)^2\ 2^{2n}} + \frac{p}{p_o} \frac{(k-1)}{k} \qquad \ldots.(3.27)$$

The value of a_o can be found from the boundary condition $\theta=0$ at $r=R$ (where R is the radius of the assumed cylindrical volume). Thus at $r=R$:

$$0 = a_o \sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}R)^{2n}}{(n!)^2\ 2^{2n}} + \frac{p}{p_o}\frac{(k-1)}{k}$$

Rearranging:

$$a_o = - \frac{1}{\displaystyle\sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}R)^{2n}}{(n!)^2\ 2^{2n}}} \frac{p}{p_o}\frac{(k-1)}{k}$$

Substituting for a_o in equation yields:

$$\theta = \frac{p}{p_o}\frac{(k-1)}{k} \left[1 - \frac{\displaystyle\sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}r)^{2n}}{(n!)^2\ 2^{2n}}}{\displaystyle\sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}R)^{2n}}{(n!)^2\ 2^{2n}}} \right] \quad .....(3.28)$$

The series:

$$\sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}r)^{2n}}{(n!)^2\ 2^{2n}} \quad \text{and}$$

$$\sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}R)^{2n}}{(n!)^2\ 2^{2n}}$$

are Bessel functions[89, 90] of order zero and can be written as:

$$J_o(A^{\frac{1}{2}}r) = \sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}r)^{2n}}{(n!)^2\ 2^{2n}}$$

$$J_o(A^{\frac{1}{2}}R) = \sum_{n=0}^{\infty} \frac{(-1)^n (A^{\frac{1}{2}}R)^{2n}}{(n!)^2\ 2^{2n}}$$

Substitution into equation 3.28 yields:

$$\theta = \frac{p}{p_o}\,\frac{(k-1)}{k}\left[1 - \frac{J_o(A^{\frac{1}{2}}r)}{J_o(A^{\frac{1}{2}}R)}\right] \qquad \ldots\ldots(3.29)$$

Substituting this value of θ in the original compression equation 3.16 gives:

$$\frac{p}{p_o} = S + \frac{p}{p_o}\,\frac{(k-1)}{k}\left[1 - \frac{J_o(A^{\frac{1}{2}}r)}{J_o(A^{\frac{1}{2}}R)}\right]$$

Hence

$$S = \frac{p}{p_o}\left[1 - \frac{(k-1)}{k}\left(1 - \frac{J_o(A^{\frac{1}{2}}r)}{J_o(A^{\frac{1}{2}}R)}\right)\right]$$

$$= \frac{p}{p_o}\left[k - (k-1)\left[1 - \frac{J_o(A^{\frac{1}{2}}r)}{J_o(A^{\frac{1}{2}}R)}\right]\right] \qquad \ldots(3.30)$$

The value of S is however, a function of r. The mean value of S can be found by replacing $J_o(A^{\frac{1}{2}}r)$ by its mean value over the cross section[90]. Such that:

$$\overline{J_o(A^{\frac{1}{2}}r)}\ \text{(mean value)} = \frac{1}{\pi R^2}\int_0^R J_o(A^{\frac{1}{2}}r)\, 2\pi r\, dr \qquad \ldots(3.31)$$

This integral can be evaluated with the aid of a well known property of the Bessel function. Namely:

$$\int_0^a x\, J_o(x)\, dx = \Big|\, x\, J_1(x)\,\Big|_0^a = a\, J_1(a) \qquad \ldots.(3.32)$$

where J_1 represents the Bessel function of order unity. Rewriting equation 3.31 in a form similar to equation 3.32 and evaluating gives:

$$\overline{J_o(A^{\frac{1}{2}}r)} = \frac{2}{R^2}\int_0^R \frac{A^{\frac{1}{2}}}{A^{\frac{1}{2}}}\, r\, J_o(A^{\frac{1}{2}}r)\, dr$$

$$= \frac{2}{A^{\frac{1}{2}} R}\; J_1(A^{\frac{1}{2}}R)$$

The Bessel function of order unity in general terms can be represented as[89, 90]:

$$J_1(x) = \frac{x}{2} - \frac{x^3}{2^3\ 1!\ 2!} + \frac{x^5}{2^5\ 2!\ 3!} - \frac{x^7}{2^7\ 3!\ 4!} + \ldots\ldots\ldots$$

Thus:

$$J_1(A^{\frac{1}{2}}R) = \frac{A^{\frac{1}{2}}R}{2} - \frac{(A^{\frac{1}{2}}R)^3}{16} + \frac{(A^{\frac{1}{2}}R)^5}{384} - \frac{(A^{\frac{1}{2}}R)^7}{18432} + \ldots\ldots$$

Substituting for $J_o(A^{\frac{1}{2}}r)$ in equation 3.30 yields:

$$S = \frac{p}{p_o}\left[k - (k-1)\left(1 - \frac{2}{A^{\frac{1}{2}}R}\ \frac{J_1(A^{\frac{1}{2}}R)}{J_o(A^{\frac{1}{2}}R)}\right)\right] \qquad \ldots.(3.33)$$

Now:

$$\frac{J_1(A^{\frac{1}{2}}R)}{J_o(A^{\frac{1}{2}}R)} = \frac{\frac{A^{\frac{1}{2}}R}{2} - \frac{(A^{\frac{1}{2}}R)^3}{16} + \frac{(A^{\frac{1}{2}}R)^5}{384} - \frac{(A^{\frac{1}{2}}R)^7}{18432} + \ldots\ldots\ldots\ldots}{1 - \frac{(A^{\frac{1}{2}}R)^2}{4} + \frac{(A^{\frac{1}{2}}R)^4}{64} - \frac{(A^{\frac{1}{2}}R)^6}{2304} + \ldots\ldots\ldots\ldots}$$

$$= \frac{\frac{A^{\frac{1}{2}}R}{2}\left[1 - \frac{(A^{\frac{1}{2}}R)^2}{8} + \frac{(A^{\frac{1}{2}}R)^4}{192} - \frac{(A^{\frac{1}{2}}R)^6}{9216} + \ldots\ldots\ldots\right]}{\left[1 - \frac{(A^{\frac{1}{2}}R)^2}{4} + \frac{(A^{\frac{1}{2}}R)^4}{64} - \frac{(A^{\frac{1}{2}}R)^6}{2304} + \ldots\ldots\ldots\right]}$$

Since $A = -\frac{jwk}{D}$, at high frequency (above 1000 Hz) the above expression can be approximated as:

$$\frac{J_1(A^{\frac{1}{2}}R)}{J_o(A^{\frac{1}{2}}R)} = \frac{1}{2}A^{\frac{1}{2}}R$$

Substitution into equation 3.33 gives:

$$S = \frac{p}{p_o}\left[k - (k-1)\left(1 - \frac{2}{A^{\frac{1}{2}}R}\ \frac{A^{\frac{1}{2}}R}{2}\right)\right]$$

$$= k\frac{p}{p_o}$$

This can be rearranged and substituted for S in terms of density to give:

$$\rho = \rho_o \left(1 + k\frac{p}{p_o}\right) \qquad \text{.........(3.34)}$$

as the equation of state.

3.3.4. Equation of Motion

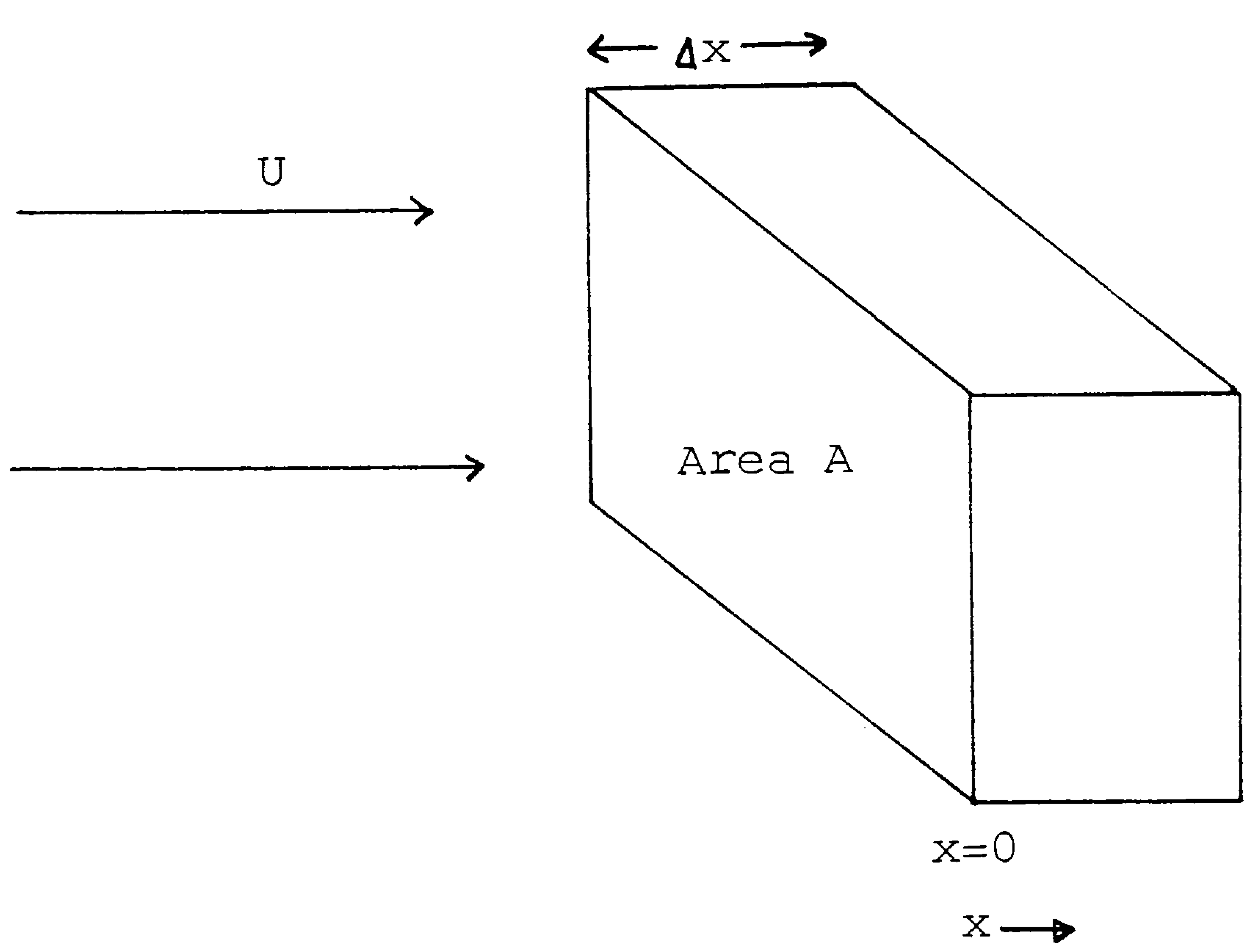


Figure 3.5 Motion of fluid through a volume element

Let p be the average variational pressure over one of the faces of area A of the volume in figure 3.5 of the material. The net force applied to the volume is thus:

$$pA - \left(p + \frac{\partial p}{\partial x}\Delta x\right) A = - \frac{\partial p}{\partial x} A \Delta x \qquad \ldots\ldots\ldots\ldots(3.35)$$

where Δx is the thickness of the volume element. Now this force will be opposed by the product of sum of the respective masses and the acceleration of the air and the solid material (fibres) in the volume element; and by a force dependent on friction. The dynamic forces on the areas S_1 (area of open space in the volume element) and S_2 (area of solid material in the volume element) at x=0 respectively are:

$$pS_1 = \underbrace{\rho_1 S_1 \Delta x \frac{\partial U_1}{\partial t}}_{\text{mass reaction force}} + \underbrace{RS_1 \Delta x (U_1 - U_2)}_{\text{frictional force}} \qquad \ldots.(3.36)$$

$$pS_2 = \rho_2 S_2 \Delta x \frac{\partial U_2}{\partial t} + RS_1 \Delta x (U_2 - U_1) \qquad \ldots.(3.37)$$

where U_1 and U_2 are the average velocities of the particle motion through the open space and the material in the volume element, ρ_1 and ρ_2 are the average densities of the air and the solid material (fibre) respectively and R is the air flow resistivity(91) (air flow resistance per unit thickness of material, which can be measured by normal air flow resistance apparatus). Because of Newtons third law, the same term for friction (as in equation 3.36) but with an opposite sign also occurs in the equation of motion of solid material (equation 3.37). The total force acting on the volume element ($A\Delta x$) was given in equation 3.35 and is equal to the sum of the forces pS_1 and pS_2. Thus:

$$-\frac{\partial p}{\partial x} A \Delta x = \rho_1 S_1 \Delta x \frac{\partial U_1}{\partial t} + \rho_2 S_2 \Delta x \frac{\partial U_2}{\partial t} \qquad \ldots.(3.38)$$

Also:

$$AU = S_1 U_1 + S_2 U_2 \qquad \ldots.(3.39)$$

where U is the average velocity of particle motion through the face A of the volume element.

U_1 and U_2 can be eliminated from equations 3.36 to 3.39 and an expression obtained containing U alone. If steady state conditions are assumed then $\frac{\partial}{\partial t}$ can be replaced by jw (as before). Rewriting and equating equations 3.36 and 3.37, yields:

$$jw\rho_1 U_1 + R(U_1 - U_2) = jw\rho_2 U_2 - R\frac{S_1}{S_2}(U_1 - U_2)$$

$$U_2\left[jw\rho_2 + R\frac{S_1}{S_2} + R\right] - U_1\left[jw\rho_1 + R\frac{S_1}{S_2} + R\right] = 0$$

$$U_2 = U_1 \frac{jw\rho_1 + R(1 + \frac{S_1}{S_2})}{jw\rho_2 + R(1 + \frac{S_1}{S_2})}$$

For convenience let:

$$X = \frac{jw\rho_1 + R(1 + \frac{S_1}{S_2})}{jw\rho_2 + R(1 + \frac{S_1}{S_2})} = \frac{Y}{Z}$$

$$U_2 = U_1 X$$

Substituting for U_2 in equation 3.39 yields:

$$U_1(S_1 + S_2 X) = AU$$

Therefore:

$$U_1 = \frac{A}{(S_1 + S_2 X)} U \qquad \text{.........(3.40)}$$

hence:

$$U_2 = \frac{AX}{(S_1 + S_2 X)} U \qquad \text{.........(3.41)}$$

Rewriting equation 3.38 and substituting for U_1 and U_2 yields:

$$-\frac{\partial p}{\partial x} A = jw\rho_1 S_1 U_1 + jw\rho_2 S_2 U_2$$

$$-\frac{\partial p}{\partial x} A = jw\rho_1 S_1 \frac{A}{(S_1 + S_2X)} U + jw\rho_2 S_2 \frac{AX}{(S_1+S_2X)} U$$

$$-\frac{\partial p}{\partial x} = jwU \left[\rho_1 S_1 \frac{1}{(S_1+S_2X)} + \rho_2 S_2 \frac{X}{(S_1+S_2X)} \right]$$

But $X = \frac{Y}{Z}$

therefore:

$$-\frac{\partial p}{\partial x} = jwU \frac{\left[\rho_1 S_1 Z + \rho_2 S_2 Y\right]}{\left[S_1 Z + S_2 Y\right]}$$

Substituting for Y and Z and separating the real and imaginary parts of the bracket:

$$-\frac{\partial p}{\partial x} = \frac{-w^2\left[(\rho_1 \rho_2 RS_2 A^3 - RS_2 A(\rho_1 S_1 + \rho_2 S_2)(\rho_2 S_1 + \rho_1 S_2)\right]}{\left[R^2 A^4 + w^2 S_2^2 (S_1\rho_2 + S_2\rho_1)^2\right]} U$$

$$+ jw \frac{\left[R^2 A^3 (\rho_1 S_1 + \rho_2 S_2) + w^2 \rho_1 \rho_2 S_2^2 A (S_1\rho_2 + S_2\rho_1)\right]}{\left[R^2 A^4 + w^2 S_2^2 (S_1\rho_2 + S_2\rho_1)^2\right]} U$$

This expression can be simplified considerably by assuming that the density of air (ρ_1) is very small compared with the density of the fibres (ρ_2) and using the following expressions for S_1 and S_2:

$$h \text{ (porosity)} = \frac{\text{volume of open space in the material}}{\text{total volume}}$$

$$= \frac{S_1 \Delta x}{A \Delta x}$$

Therefore: $S_1 = hA$

and $S_2 = (A-S_1) = A(1-h)$

Thus:

$$-\frac{\partial p}{\partial x} = \frac{w^2 \rho_2^2 Rh(1-h)}{R^2+w^2(1-h)^2(\rho_2 h+\rho_1)^2}$$

$$+ \quad jw\frac{\rho_2(1-h)\left[R^2+w^2\rho_1(h\rho_2-h^2\rho_2+\rho_1)\right]}{R^2+w^2(1-h)^2(\rho_2 h+\rho_1)^2}$$

This equation can be rewritten as:

$$-\frac{\partial p}{\partial x} = Y_r U + jY_i U$$

where

$$Y_r = \frac{w^2\rho_2^2 Rh(1-h)}{\left[R^2+w^2(1-h)^2(\rho_2 h+\rho_1)^2\right]}$$

$$Y_i = \frac{w\rho_2(1-h)\left[R^2+w^2\rho_1(h\rho_2-h^2\rho_2+\rho_1)\right]}{\left[R^2+w^2(1-h)^2(\rho_2 h+\rho_1)^2\right]}$$

Hence the equation of motion is:

$$-\frac{\partial p}{\partial x} = Y_r U + jY_i U \qquad \text{..........(3.42)}$$

3.3.5. The Wave Equation and The Attenuation Constant

In the last few sections the following equations were derived:

$$\rho_o \frac{\partial V_s}{\partial x} = -h\frac{\partial \rho}{\partial t} \quad \text{as the equation of continuity (3.10)}$$

$$\rho = \rho_o(1 + k\frac{p}{p_o}) \quad \text{as the equation of state (3.34)}$$

$$-\frac{\partial p}{\partial x} = Y_r + jY_iU \quad \text{as the equation of motion (3.42)}$$

In order to obtain the wave equation, equation 3.10 and 3.34 are first solved together. Differentiating equation 3.34 with respect to time:

$$\frac{\partial \rho}{\partial t} = k\frac{\rho_o}{p_o}\frac{\partial p}{\partial t}$$

and substituting into equation 3.10:

$$-\rho_o\frac{\partial V_s}{\partial x} = hk\frac{\rho_o}{p_o}\frac{\partial p}{\partial t}$$

or

$$-\frac{\partial V_s}{\partial x} = \frac{hk}{p_o}\frac{\partial p}{\partial t}$$

As before replacing $\frac{\partial}{\partial t}$ with jw, gives:

$$-\frac{\partial V_s}{\partial x} = \frac{hk}{p_o}jwp \qquad \text{..........(3.43)}$$

since V_s (average velocity of the fluid particles) is equal to U, the above equation can be rewritten as:

$$-\frac{\partial U}{\partial x} = \frac{hk}{p_o}jwp \qquad \text{..........(3.43)}$$

U now can be eliminated from equations 3.42 and 3.43, by differentiating equation 3.42 with respect to x and substituting for $\frac{\partial u}{\partial x}$ in equation 3.43. This yields:

$$-\frac{\partial^2 p}{\partial x^2} = \left[Y_r + jY_i\right]\frac{\partial U}{\partial x}$$

$$-\frac{\partial^2 p}{\partial x^2} = (Y_r + j Y_i) \frac{kh}{p_o} jwp \qquad \text{.........(3.44)}$$

This equation has a solution[92] for the x dependence of p (as mentioned earlier, equation 3.7 and 3.8), of the form:

$$p(x,t) = A_1 \exp (jwt - \gamma x)$$

where γ is equal to the propagation constant and A_1 is equal to the amplitude of the wave. Differentiating the above equation twice with respect to x gives:

$$\frac{\partial^2 p}{\partial x^2} = \gamma^2 A_1 \exp(jwt - \gamma x)$$

$$= \gamma^2 (p(x,t))$$

Substituting for $\frac{\partial^2 p}{\partial x^2}$ in equation 3.44 gives:

$$\gamma^2 p = (Y_r + j Y_i) \frac{kh}{p_o} jwp$$

$$\text{or} \quad \gamma^2 = Y_r (jwk \frac{h}{p_o}) - Y_i wk \frac{h}{p_o} \qquad \text{.......(3.45)}$$

But by definition: $\gamma = \alpha + j\beta$

$$\text{or} \quad \gamma^2 = \alpha^2 + 2j\alpha\beta - \beta^2 \qquad \text{..(3.46)}$$

By equating the real and imaginary parts of equations 3.45 and 3.46 and simplifying, the following equation for the attenuating constant (α) was obtained:

$$\alpha = \left[\frac{wkh}{2p_o} (- Y_i + (Y_r^2 + Y_i^2)^{\frac{1}{2}}) \right]^{\frac{1}{2}}$$

Hence substitution of the attenuating constant (α) in equation 3.6, yields the transmission loss (ΔL) for a fabric of thickness (Δx).

3.3.6 Summary

In the last few sections, from the equation of continuity (3.10), state (3.34) and motion (3.42), an expression for the attenuating constant (α) was derived, namely:

$$\alpha = \left[\frac{wkh}{2p_o} \left[-Y_i + (Y_i^2 + Y_r^2)^{\frac{1}{2}} \right] \right]^{\frac{1}{2}}$$

where as mentioned earlier:

$w = 2\pi$ frequency

p_o = atmospheric pressure

h = porosity

$k = 1.4$

$$Y_i = \frac{w\rho_2(1-h)\left[R^2 + w^2\rho_1(h\rho_2 - h^2\rho_2 + \rho_1)\right]}{R^2 + w^2(1-h)^2(\rho_2 h + \rho_1)^2}$$

$$Y_r = \frac{w^2\rho_2^2 Rh(1-h)^2}{R^2 + w^2(1-h)^2(\rho_2 h + \rho_1)^2}$$

R = air resistance per unit length (specific resistance)

ρ_1 = density of air

ρ_2 = density of fibre

The acoustic transmission loss as a result of the fabric being present in the sound path can be computed with the help of this constant, using the expression:

$$\text{Transmission Loss} = 8.69\,\Delta x\,\alpha \qquad \text{........(3.47)}$$

(derived earlier), where:

Δx = thickness of the fabric.

CHAPTER FOUR

PRODUCTION AND TESTING OF NEEDLE-FELTED FABRICS

4.1. Introduction

In the previous chapter the general theory of sound absorption by porous fabrics was developed. In terms of the equation deduced particular attention, subsequently was directed towards the use of such materials as loudspeaker covers and porous attenuating partitions. The purpose of this chapter, therefore is to give a description of how the fabrics used were produced and tested for their acoustic properties (transmission loss). From the experimental point of view the work divides into three parts. The first part involves the production of the needle-felted fabrics from fibre webs, the second part involves the measurement of fabric properties such as thickness, weight per unit area and air flow resistance and finally the third part involves the measurement of acoustic transmission loss as a result of the fabric being present in the sound path. The three parts are quite different in nature and as such the description of the experimental work must be devided into three parts.

4.2. Production of Needle-Felted Fabrics

4.2.1. Introduction

A needle-punched fabric or a needle-felt is a non-woven fabric in which the fibres are interlocked and entangled by means of a punching operation using barbed needles to produce a felt-like fabric from any type of natural or man-made fibre. Needling is one of the oldest and the most commonly used mechanical methods of producing non-woven fabrics.

As in the case of other non-woven fabrics, significant developments have occured in recent years in the production of higher quality needle-felted fabrics with improved aesthetics. As well as the commercial development in machine and production techniques, a considerable amount of fundamental research has taken place in a number of centres and this has resulted in a clarification of the factors affecting the structure and the behaviour of needle-felted fabrics[93,94]. There are various types of needling processes. Vertical needling from above or below is the most common method. The main advantage of this method is the simplicity of the machine construction and the long life of the needles.

4.2.2. Principles of Needle-Felted Fabric Production

The production of needle-felted fabrics can be divided into three stages:

(a) Opening and blending of fibres;

(b) Web formation; and

(c) Needling of the web.

(a) Opening and Blending of Fibres

The opening and blending operations are similar to those used in conventional spinning system and the choice of suitable machinery depends on the type of fibres to be processed, and on the degree of openness, cleanliness and blending required.

(b) Web Formation

Cotton cards, woollen cards and garnetts can be used for web formation. Garnetts are usually inferior to cards, but they are capable of running at high speed and can handle a greater variety of fibres. A single card web is not thick enough so that several layers are required to give sufficent thickness and strength to the web. The web can be made by several methods depending on the weight and type of fabric required. In the present work the web was formed by a method known as parallel-laid web.

This method was developed to prepare a condensed card web which has fibres relatively randomised and entangled in a homogeneous structure throughout the web. In this method the web is formed by collecting the card web coming out from the doffer on to a wooden roller as shown in figure 4.1. The webs comming out from the card are rolled over each other to give the condensed web. The weight per unit area of the condensed web can be varied by varying the

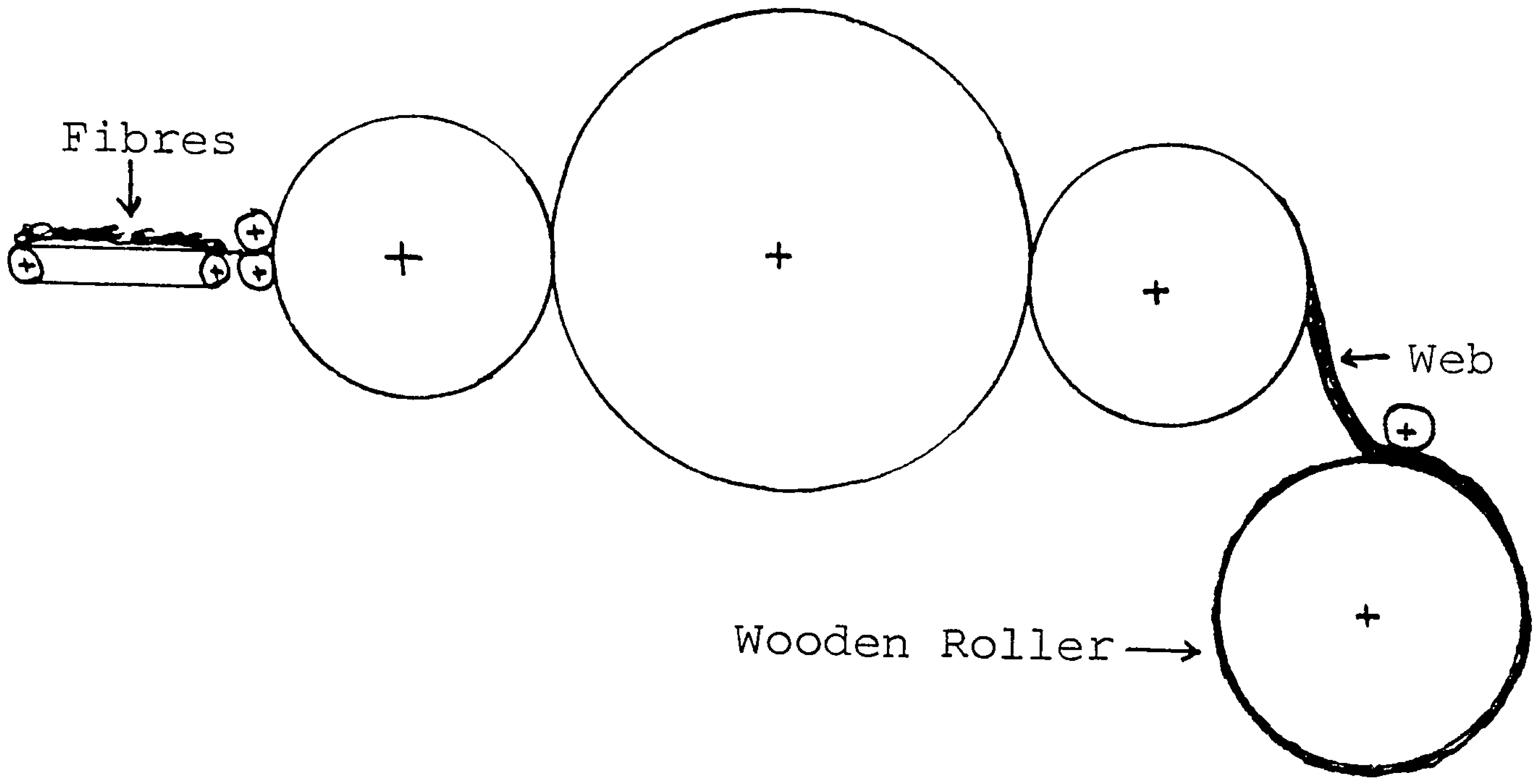


Figure 4.1 Schematic arrangement of a system for the production of parallel-laid web

number of revolutions of the wooden roller in figure 4.1. When the required weight of the web has been collected on to the wooden roller, the wrapped web is cut across the width and opened out to give a rectangular sample.

(c) Needling of The Web

The fibrous web, produced by the method described in the last section, is mechanically bonded by passing it through a needle-loom. In the needle-loom the web is subjected to a mechanical action in which many needles entangle and interlock the fibres to produce a felt-like fabric. The main feature of the needle-loom is the punching action of a number of steel barbed needles mounted on a needle board which reciprocates up and down and re-orientes the fibres into a loop. Thus individual fibres interlock with each other partially by the frictional force with the surrounding fibres and partially by interfibre entanglement.

As the fibre length is large compared with the felt thickness, it is quite possible that one fibre can be drawn into more than one loop to give extra bonding. When the needles start to withdraw from the batt, the fibres which have been pushed down in the formation of the vertical loop become unlocked from the barbs. By repeating this punching action many times within each unit area of the the batt, fabrics with a wide variety of properties can be produced.

The principal working parts common to all needle-looms are shown schematically in figure 4.2. These may be discussed as follows:

Felting Needles

Felting needles usually have a triangular blade cross-section, although needles with round or square-shaped cross-section are also available. Three barbs are usually located on each edge of the triangular blade, but needles with as many as five and as few as one barb per edge have been produced for some special purposes. Needles are made with three types of barb spacing: that is, regular barbed needles, which have their barbs 0·25 inches apart; medium barbed needles having a spacing of 0·187 inches; and close barbed needles having their barbs 0·125 inches apart in each row. The depth of the barb is very important when considering felting efficiency. if a barb is too shallow it will not pick up sufficient fibres; but if the barb is too deep, needle breakage, fibre breakage and tearing of the material will occur.

The needles are made in single or double blade constructions. A single blade needle has a large diameter shank and a smaller diameter working part which carries the barbs. A double blade needle has a large diameter shank followed by a smaller diameter intermediate blade and an even smaller diameter working part. The rate of needle wear is dependent on the type of material being processed, the thickness and density of the final product, and the needle construction and type of finish applied to the needle. Needle damage particularly depends upon needle straightness and the amount of wear on the holes in the needle board. Due

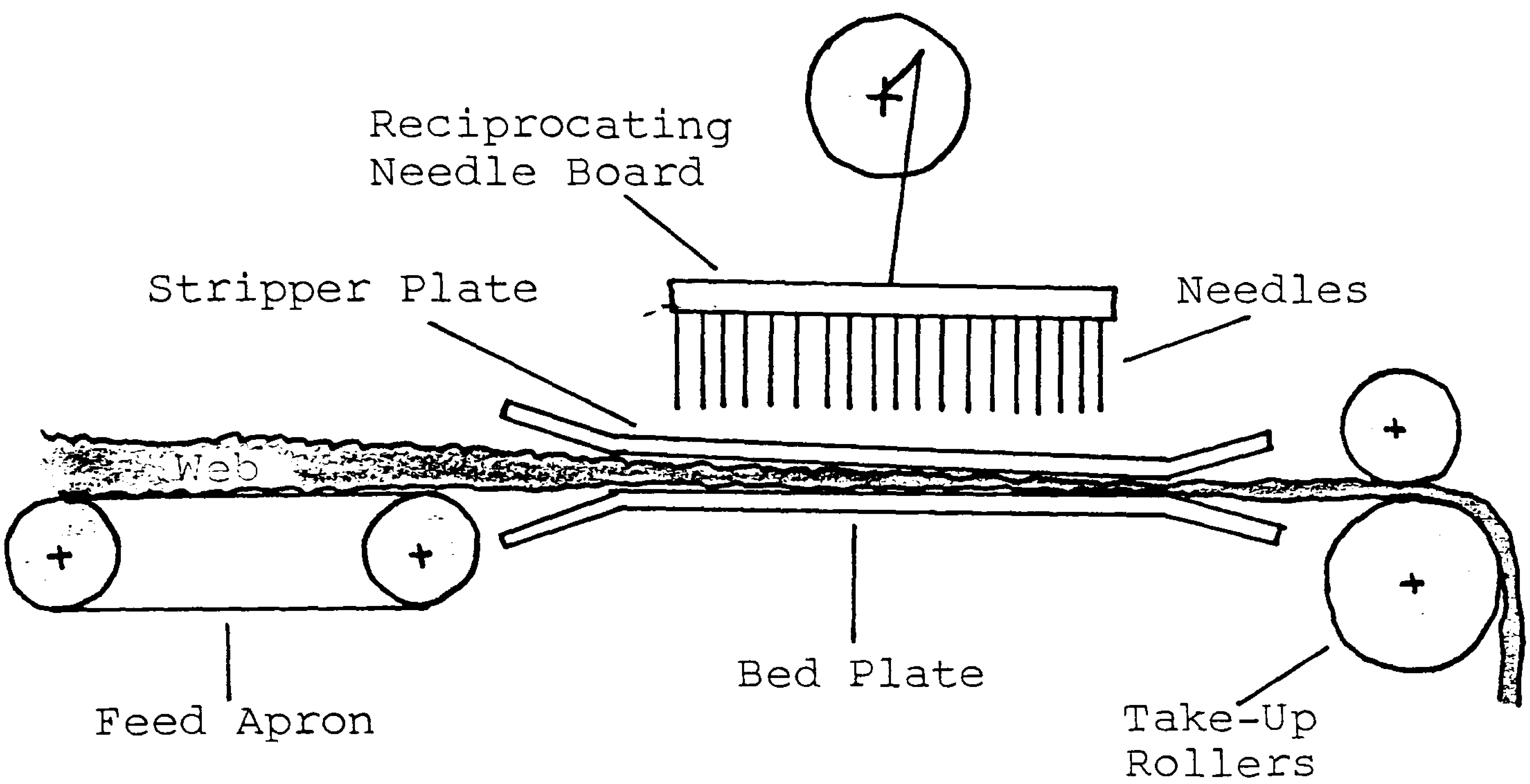


Figure 4.2a Movement of the web after withdrawal of Needles

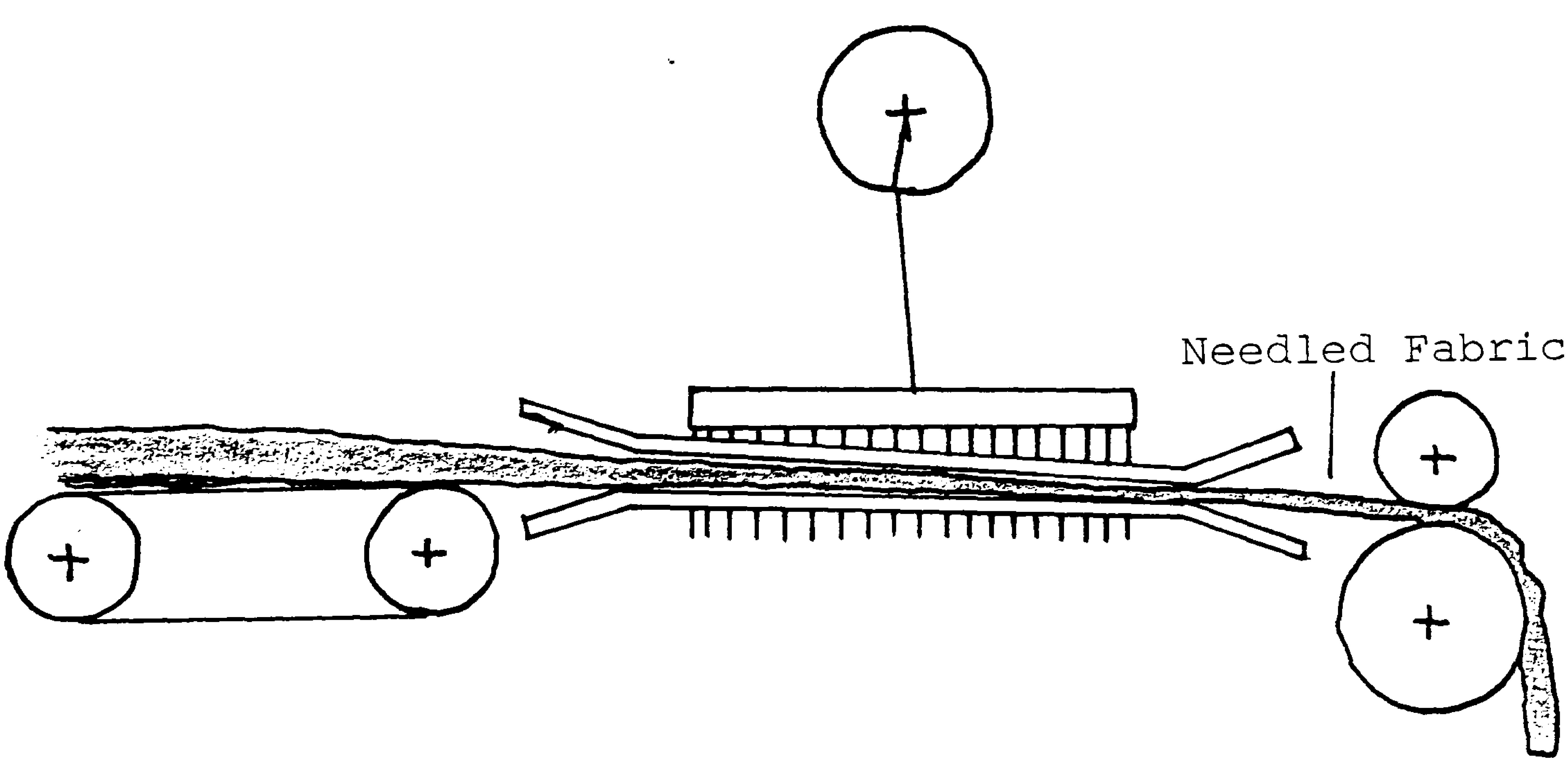


Figure 4.2b Needling action while the web is stationary

to needle wear, it is common practice commercially to change a number of rows of needles in rotation, after a specified number of machine running hours[95].

Bed and Stripper Plate

These two plates form a confining area through which the web of loose fibres is moved during needling. Both of the plates have matching holes through which needles pass. The stripper plate strips the needles of any fibres. The height of the stripper plate from the bed plate must be adjusted according to the thickness of the fabric being produced.

Needle Board

This metallic board carries the needles and is moved up and down in the machine by a system of cranks. The needles are located in holes and held in position by plastic plugs.

Feed and Fabric Take-Up

The feed apron is an endless conveyor which delivers the web of loose fibres to the punching area. The take-up roller, on the other side of the punching area, pulls the web through the space between the plates every time the needles are withdrawn. The movement of both the feed apron and the take-up roller is intermittent to allow stopping of the web during the punching and withdrawal of the needles as in figure 4.2.

4.2.3. Needle-Loom Variables

Needle Penetration Through The Web

This is adjusted by raising or lowering the bed of the machine carrying the web with the stroke of the needles remaining constant. The raising of the web increases the depth of penetration, which is indicated on a scale fixed to the machine.

Speed of Needling

Increasing this speed increases the productivity of the machine for the same amount of needling per unit area of the fabric.

Distance Between Stripper and Bed Plate

This adjustment should be such that the fabric does not vibrate during needling. The vertical oscillation of the fabric due to too wide a space greatly weakens the needled fabric. The stripper plate is always set at an angle to the bed plate to compensate for the thicker web at the input.

Web Speed

The actual movement of the web through the needling area is done by the pull of the take-up roller. Accordingly, the amount of needling per unit area of the web is controlled by the speed of the take up roller to compensate for the stretch or contraction occuring during the needling action.

4.2.4. Fabric Production

The fibres listed in table 4.1 used in the present work were opened by hand. In order to produce a parallel-laid web, a measured quantity of the fibres was placed on the feed lattice of a Haigh Sample Carder and the resulting web was collected on a wooden drum fitted at front of the card and driven from the doffer so that their surface speeds were approximately the same. The collected web was cut across the width and opened out to give a rectangular sample, which was folded into two and was passed through the card once again. The new collected web subsequently was cut across the width and opened out to give a rectangular sample of parallel laid web. The web then was needled on a needle-loom. The details and settings of the machine are listed in table 4.2.

Before the web was inserted into the machine the needles and the stripper bed were lifted to their top-most position. The tip of the web was placed by hand on top of a previously needled fabric gripped between the take-up rollers. Both the web and part of the fabric were needled several times, each time reversing the faces until the required properties were obtained. The needled fabrics

Fibre Identification	Fibre Type		Source
	Material	Fineness (dtex)	
A	Acrylic	3.3	School of Textiles, Leicester Polytechnic.
B	Acrylic	5.0	
C	Acrylic	5.5	
D	Acrylic	9.3	
E	Acrylic	18.9	
F	Acrylic	1.3	Monsanto Textiles, Leicester.
G	Acrylic	2.5	
H	Acrylic	3.3	
I	Acrylic	5.6	
J	Acrylic	7.8	
K	Acrylic	17.0	
L	Wool		School of Textiles

Table 4.1

Needle Penetration	0.75 inch
Drive Speed	80.3 cm. min^{-1}
Needle Board Area	415 cm^2
Number Of Needles	465
Needle Density	1.12 Needles.cm^{-2}
Needling Speed	275 Penetrations. min^{-1} or 3.4 Pen. Per cm Movement
Amount Of Needling Per Passage	43.7 Needles Per cm Per Passage
Needle Gauge	13/R/NP/BP Barb Close

Table 4.2

thus produced had a felt-like appearance and their structure was reasonably consolidated.

4.3. Fabric Testing

4.3.1. Introduction

Before testing, the fabrics were allowed sufficient time to achieve equilibrium with the prevailing atmospheric conditions. Although the temperature remained approximately constant at $20^{\circ}C$ relative humidity control was not possible. The weight per unit area, thickness and air resistance of the fabrics subsequently was measured, and the value of porosity for each fabric was calculated.

4.3.2. Measurement Of Weight Per Unit Area And Thickness

For the measurement of weight per unit area a specimen of known area was marked and cut from the fabrics produced as described in the last section using a marking pen, cardboard template and shears. The specimen was cut so that its length was parallel to the needling machine direction. Each cut specimen was weighed on a balance with a senstivity of 0·001g and the fabric weight in gm^{-2} was calculated.

The thickness of the fabric was measured on a 'Essdiel thickness gauge'. On this the thickness is indicated on a large dial gauge with a range of 0-25mm and graduations of 0·01mm. The point of exact thickness is shown by a light powered by a built in battery unit. The foot of the gauge was modified to give an area of $200cm^{2}$ under a pressure of 0·01 Nm^{-2}. This pressure was found suitable for such compressible fabrics. At least ten readings of thickness were taken in different places of the fabric and the mean of these values calculated. The coefficient of variation of thickness was found to be in the range 1-2%.

The weight per unit area and thickness of each fabric is listed in table 4.3.

Fabric	Fibre	Weight Per Unit Area (gm^{-2})	Thickness (mm)	Air Flow Resistance (Nsm^{-3})	Porosity
A1	A	91.35	4.92	65.54	0.9840
A2	A	103.70	5.47	71.22	0.9837
A3	A	123.24	6.32	86.44	0.9832
A4	A	153.29	8.22	102.50	0.9837
A5	A	164.24	7.50	99.76	0.9811
A6	A	135.37	5.56	85.12	0.9790
A7	A	131.76	6.47	87.51	0.9824
A8	A	146.06	6.18	92.21	0.9796
A9	A	153.06	6.90	98.59	0.9809
A10	A	185.76	7.76	106.54	0.9794
A11	A	214.70	8.42	119.33	0.9780
B1	B	95.24	5.21	52.17	0.9842
B2	B	168.38	7.97	80.19	0.9818
B3	B	152.15	7.32	76.32	0.9821
B4	B	204.08	8.68	90.93	0.9797
B5	B	216.90	9.73	101.45	0.9808
B6	B	272.15	10.69	115.22	0.9780
B7	B	249.43	10.10	114.68	0.9787
B8	B	336.00	11.38	128.05	0.9746
C1	C	87.17	4.66	43.57	0.9839
C2	C	88.89	5.02	47.09	0.9847
C3	C	148.22	6.22	61.80	0.9795
C4	C	104.22	4.18	45.56	0.9785
C5	C	120.33	5.52	54.46	0.9812
C6	C	165.22	7.91	75.47	0.9820
C7	C	127.11	6.71	60.68	0.9837
C8	C	181.44	7.50	73.67	0.9791
C9	C	126.17	4.95	51.17	0.9780
C10	C	179.72	6.78	69.52	0.9772
C11	C	162.72	5.98	65.37	0.9765
C12	C	186.22	8.72	81.90	0.9816
C13	C	215.89	8.46	83.36	0.9780

Table 4.3

Fabric	Fibre	Weight Per Unit Area (gm^{-2})	Thickness (mm)	Air Flow Resistance (Nsm^{-3})	Porosity
C14	C	198.44	6.59	72.82	0.9740
C15	C	171.00	5.74	67.54	0.9743
C16	C	116.83	5.00	51.61	0.9799
C17	C	126.06	6.09	58.23	0.9822
C18	C	247.33	9.99	96.48	0.9787
C19	C	146.06	5.72	57.26	0.9730
C20	C	155.28	6.67	64.69	0.9799
C21	C	87.06	4.90	45.90	0.9847
C22	C	86.72	4.47	43.26	0.9833
C23	C	96.33	5.47	49.44	0.9848
C24	C	107.00	4.56	47.45	0.9798
C25	C	161.22	7.20	69.98	0.9807
C26	C	150.56	6.14	63.32	0.9789
C27	C	120.78	5.34	52.14	0.9805
C28	C	189.11	8.17	78.53	0.9801
C29	C	128.39	4.80	49.84	0.9769
C30	C	177.94	6.92	71.38	0.9778
C31	C	193.11	6.25	73.58	0.9734
C32	C	228.22	10.09	93.13	0.9805
C33	C	123.94	6.19	58.52	0.9826
C34	C	177.17	6.32	68.39	0.9758
C35	C	207.50	7.56	78.59	0.9763
C36	C	207.22	7.16	77.28	0.9751
D1	D	139.24	5.56	51.89	0.9784
D2	D	161.21	6.25	60.02	0.9788
D3	D	187.40	6.59	63.28	0.9755
D4	D	238.34	7.46	72.53	0.9725
D5	D	259.40	8.12	78.84	0.9725
D6	D	275.55	8.49	83.58	0.9720
D7	D	326.72	9.29	92.10	0.9697

<u>Table 4.3</u> (continued)

Fabric	Fibre	Weight Per Unit Area (gm^{-2})	Thickness (mm)	Air Flow Resistance (Nsm^{-3})	Porosity
E1	E	124.04	5.53	41.54	0.9807
E2	E	158.49	6.30	48.49	0.9783
E3	E	183.07	6.63	51.60	0.9761
E4	E	222.94	8.39	60.99	0.9771
E5	E	206.72	7.00	56.88	0.9745
E6	E	234.72	7.52	59.63	0.9731
E7	E	254.72	8.03	61.50	0.9727
E8	E	238.49	7.12	58.24	0.9711
E9	E	241.21	6.56	57.04	0.9683
E10	E	271.24	8.20	64.39	0.9715
E11	E	315.62	9.04	70.38	0.9699
E12	E	311.18	7.59	64.25	0.9647
F1	F	154.50	6.52	152.00	0.9796
F2	F	164.83	6.34	142.48	0.9776
F3	F	208.37	6.69	183.27	0.9732
F4	F	242.03	7.42	192.01	0.9719
F5	F	279.10	7.97	213.76	0.9698
F6	F	327.37	8.74	265.87	0.9677
G1	G	117.90	6.15	94.95	0.9835
G2	G	124.90	6.25	94.94	0.9828
G3	G	143.70	6.70	110.51	0.9815
G4	G	154.10	6.26	108.55	0.9788
G5	G	201.10	8.24	126.29	0.9790
G6	G	206.90	6.93	135.53	0.9743
G7	G	248.10	9.47	158.98	0.9774
G8	G	305.97	9.30	145.30	0.9716
G9	G	234.97	7.32	140.83	0.9713
G10	G	303.43	7.96	158.93	0.9671
G11	G	407.10	11.64	215.70	0.9699
G12	G	399.30	9.76	193.42	0.9647

Table 4.3 (continued)

Fabric	Fibre	Weight Per Unit Area (gm^{-2})	Thickness (mm)	Air Flow Resistance (Nsm^{-3})	Porosity
G13	G	362.83	8.88	194.11	0.9645
G14	G	629.07	13.41	289.02	0.9596
H1	H	165.30	7.34	97.85	0.9806
H2	H	234.30	8.96	108.94	0.9775
H3	H	286.97	9.70	132.65	0.9745
H4	H	214.77	8.01	111.06	0.9769
H5	H	287.90	9.54	141.05	0.9740
H6	H	321.57	10.20	142.84	0.9728
H7	H	398.70	11.63	177.00	0.9704
I1	I	161.37	8.04	70.61	0.9827
I2	I	179.97	8.40	73.43	0.9815
I3	I	221.97	9.65	95.16	0.9802
I4	I	248.63	10.06	82.77	0.9787
I5	I	253.17	10.30	93.02	0.9788
I6	I	317.03	10.81	104.63	0.9747
I7	I	304.10	11.14	102.83	0.9765
I8	I	416.43	13.10	119.41	0.9726
J1	J	114.97	6.75	53.12	0.9853
J2	J	148.77	8.10	62.75	0.9842
J3	J	130.17	8.38	70.61	0.9866
J4	J	158.57	8.69	69.78	0.9843
J5	J	199.90	10.42	78.93	0.9835
J6	J	210.30	9.48	77.10	0.9817
J7	J	195.17	10.13	82.20	0.9834
J8	J	232.17	11.05	86.41	0.9819
J9	J	252.63	10.83	86.45	0.9799
J10	J	291.83	11.15	91.43	0.9744
J11	J	295.57	13.11	101.96	0.9805
J12	J	307.63	11.90	95.93	0.9777
J13	J	330.17	14.34	109.21	0.9802

Table 4.3 (continued)

Fabric	Fibre	Weight Per Unit Area (gm^{-2})	Thickness (mm)	Air Flow Resistance (Nsm^{-3})	Porosity
J14	J	333.23	12.01	117.23	0.9761
J15	J	320.90	11.07	97.29	0.9750
K1	K	252.90	9.67	62.97	0.9774
K2	K	276.03	10.13	71.84	0.9765
K3	K	331.43	11.17	80.48	0.9744
K4	K	406.97	12.47	90.20	0.9719
K5	K	421.03	12.46	89.53	0.9709
K6	K	435.77	12.82	90.30	0.9707
K7	K	472.17	13.03	94.36	0.9688
K8	K	473.63	13.78	96.61	0.9748
K9	K	472.77	13.03	93.48	0.9687
L1	L	80.63	5.21	46.27	0.9882
L2	L	110.63	6.29	55.61	0.9866
L3	L	123.50	6.54	65.84	0.9856
L4	L	146.17	7.52	76.37	0.9852
L5	L	212.37	9.00	91.97	0.9820
L6	L	221.10	9.74	104.01	0.9827
L7	L	340.90	11.72	118.77	0.9778
L8	L	369.50	12.28	127.20	0.9770

Table 4.3 (continued)

4.3.3. Measurement of Air Flow Resistance

The air flow resistivity (R)[91] of any layer of porous material is defined as the air flow resistance (r) per unit thickness of material, or (as indicated in figure 4.3)

$$R = \frac{\Delta p}{\Delta x\, U} = \frac{r}{\Delta x}$$

where Δp is the applied air pressure differential measured between the two sides of the layer (Nm^{-2}), U is the air velocity through and perpendicular to the two faces of the layer (ms^{-1}) and Δx is the thickness of the layer.

The permeability of a textile fabric which is the reciprocal of its air resistance as defined above is a fundamental characteristic that has many applications other than the area of sound absorption. It is particularly useful in evaluating air filtration fabrics, parachute fabrics and mosquito nets. In apparel fabrics, air-permeability is a fabric comfort factor, the air flow through the fabric being the main source of body temperature control.

Many different instrumental techniques have been developed for the measurement of air flow through fabrics under standardised conditions[60,96,97]. The 'Shirley Air-Permeability Tester'[98], originally developed by Clayton[96], may be considered as the preferred type of instrument in which the air flow through a test specimen is measured under constant pressure drop across a fabric. A later version of this instrument was evaluated by Lord[97], who also established a number of relations between air-permeability and other fabric properties. This type of instrument was found to be unsuitable for the type of fabrics used in the present work.

A schematic representation of the apparatus used for the determination of air resistance used in the present work is given in figure 4.3. Manometer 1 measures the pressure difference (Δp) between the two sides of the sample and from the measurements of manometer 2 the air velocity through and perpendicular to the face of the sample can be calculated, using the standard formulae

$$\underset{(ms^{-1})}{\text{Velocity}} = 4\,(h)^{\frac{1}{2}}$$

where h is the pressure head in mm water gauge. From these two measurements (namely Δp and U) the flow resistance was calculated.

The air resistance for each fabric was measured at several different pressures, and was found to be velocity dependent (this fact will be discussed later on). Therefore all air resistance measurements were calculated using a constant value of pressure difference.

The air resistance for all fabrics is listed in table 4.3 (page 56).

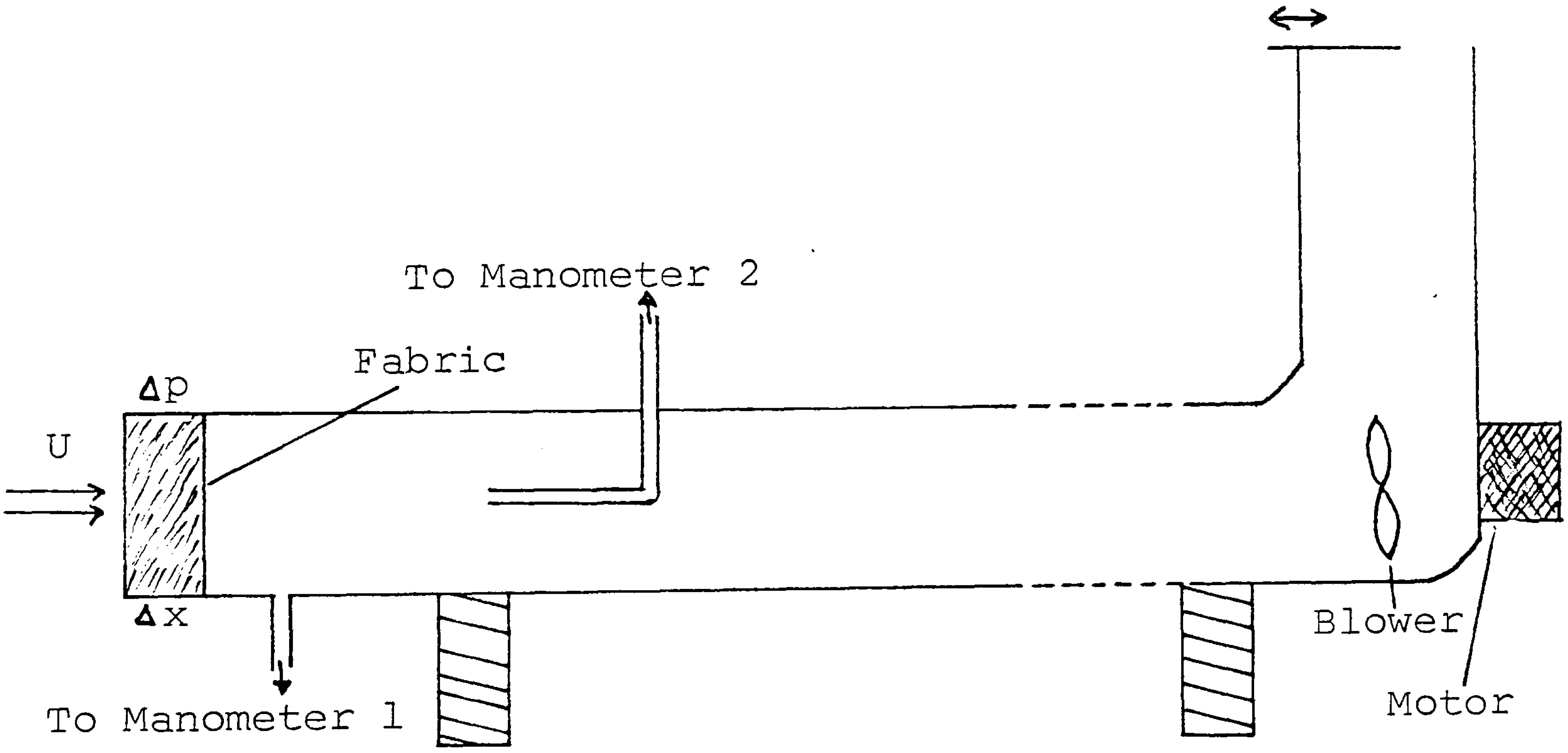


Figure 4.3 Simplified diagram of the principal involved in the measurement of air flow resistance.

4.3.4 Calculation Of Fabric Porosity

The porosity (h) of a porous material defined as the ratio of open space to the total volume of the porous material is given by:

$$h = \frac{\text{volume of open space}}{\text{total volume}}$$

$$= \frac{\text{total volume - volume of fibres}}{\text{total volume}}$$

$$= 1 - \frac{\text{volume of fibres}}{\text{total volume}}$$

$$= 1 - \frac{\dfrac{\text{weight of fibres}}{\text{density of fibres}}}{\dfrac{\text{weight of fabric}}{\text{density of fabric}}}$$

Assuming that the weight of fibres within the fabric is equal to the total weight of the fabric (that is, compared with the weight of the fibres, the weight of the air in the fabric could be neglected). Hence:

$$h = 1 - \frac{\text{density of fabric}}{\text{density of fibre}}$$

Using the above expression the porosity of each fabric was calculated and is listed in table 4.3 (page 56).

4.4. Acoustic Testing

4.4.1. Introduction

The absorption of sound by a particular material is difficult to measure precisely because, apart from the fabric variables, sound absorption also depends upon many external factors, such as the manner in which the material is presented for test, sample size, the angle of incidence of the sound wave to the fabric, the area and reflective characteristics of the test area and so on. Hence the development of a suitable test method must take into consideration or maintain at a constant value all the factors mentioned above so that a meaningful comparison between fabrics can be made.

In recent years, great interest has been shown in measuring the acoustic behaviour of materials, with particular reference to their effectiveness in reducing noise in buildings of various kinds. Methods of measuring airborne sound absorption employ either sound of fixed frequencies or a wide spectrum noise filtered into narrow bands; the technique of determining the absorption coefficient in a reverberation chamber generally being accepted as the most accurate one. An alternative technique, using an impedence tube also has found widespread use because it requires less sophisticated measuring facilities and small test specimens. However, as pointed out earlier, these methods produce different experimental values and also the testing can not be carried out "in situ". However in the present work, the loss in detected acoustic energy was measured due to absorption resulting from placing a fabric in the sound path rather then the absorption coefficient and the testing was carried out "in situ".

4.4.2. Acoustic Apparatus and Experimental Design

The basic principle involved in the measurement of transmission loss (sound absorption) is shown as a block diagram in figure 4.4. The system consists of a generator (A), capable of sweeping through a broad range of frequencies, producing a signal which is amplified (B)

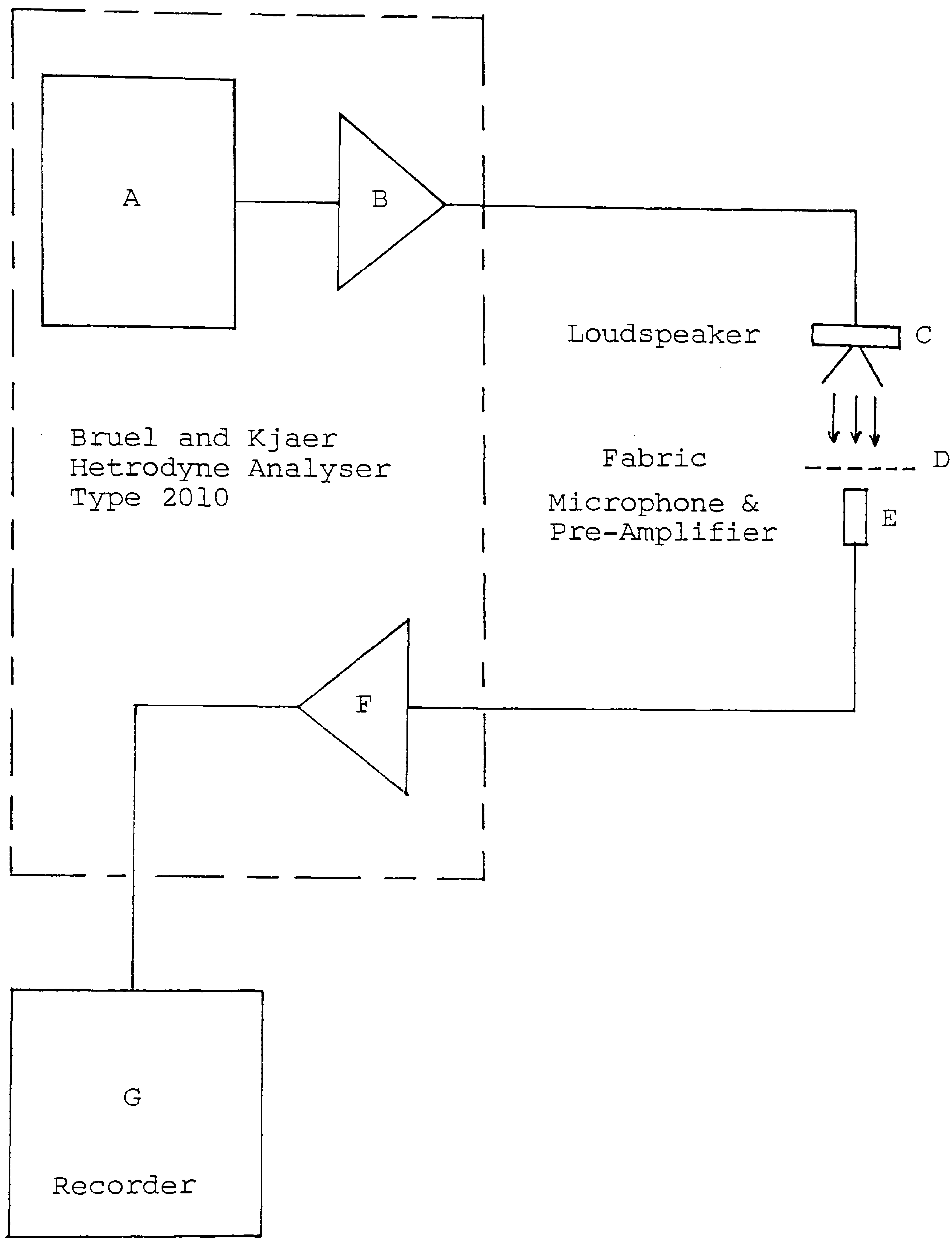


Figure 4.4. Simplified block diagram of the principal involved in the measurement of transmission loss

before being presented to a loudspeaker (C). The sound wave emitted by the loudspeaker is interrupted by placing a fabric in its sound path. Sound which passes through the fabric (D) is detected by a microphone (E) and after amplification (F) is passed to the recording device (G). The signal fed to the loudspeaker is tapped to provide a direct link to the recorder. The principal parts of the apparatus as shown in figure 4.4. may be discussed as follows.

Signal Generator

This single instrument is a Bruel and Kjaer, hetrodyne analyser type 2010 and is a constant bandwidth narrow band frequency analyser covering the frequency range 2Hz to 200kHz in three logrithmic or linear ranges with bandwidths selectable from 3.16Hz to 1kHz. Also it contains a beat frequency oscillator, the frequency of which is synchronised with the tuning frequency of the analyser. The tuned-in frequency can be read off the main frequency scale and is shown on a six digit seven segment display. There are a number of programmes in which the bandwidth and meter rectifier time constant can be controlled as a function of frequency. The measured signal is rectified by a true RMS rectifier, the indicating meter has interchangable scales and a direct indication of measuring range. Other features included are a built-in-power supply for condenser microphone assemblies, output for a recorder and a built in linear-logrithmic converter giving linear-logrithmic scaled meter readings and a direct current output signal. To obtain a graphical representation of the frequency analysis, the hetrodyne analyser can be synchronised with a Bruel and Kjaer level recorder type 2305. The hetrodyne analyser operates as an automatic tracking analyser in the frequency range 20Hz to 200kHz. This instrument locks on to and tracks the fundamental or harmonics of practically any type of periodic wave form.

A more detailed description of this instrument may be found in the Bruel and Kjaer instruction manual[99].

Speaker and Fabric Holder

In order to obtain good repetition of fabric placement in the sound path, the stand shown in figure 4.5 was constructed. The fabric being tested rests on a hardboard sheet with numerous holes drilled in it. The board has a large hole in the centre over which the fabric rests. The height of the stand can be adjusted as required and as a result the distance between fabric and the speaker can be varied.

The speaker used was a dome tweeter type having an impedence of 8 ohms. The frequency response of the speaker is shown in figure 4.6. Since the frequency range of interest is in the region of 1kHz to 20kHz, then the dome tweeter having a lower cut-off frequency of 800Hz was used.

Microphone and Pre-Amplifier

There are several factors to be considered in the selection of the most suitable microphone. Apart from environmental conditions such as temperature, humidity and wind there are also problems of stability over the frequency range, and directivity. Generally speaking, condenser type microphones show very good properties with regard to temperature and long-term stability. However from the point of view of frequency response and directivity there may not be any unique solution to the microphone problem, so that certain compromises have to be made. All these factors are interconnected and related to the physical size of the microphone. The smaller the physical dimensions of the microphone, the wider is the frequency range and so the effect of directivity is reduced.

After consideration of all the relevant information concerning microphone performance, a Bruel and Kjaer type 4113 half-inch diameter condenser microphone was chosen for this work. The diaphragm of the microphone is made of pure Nickel and the back plate and the housing are made of high-Nickel alloy. This practically elliminates variation of senstivity with temperature. Also, special care has been devoted to the equilisation of the static air pressure between the inside and the outside of the cartridge

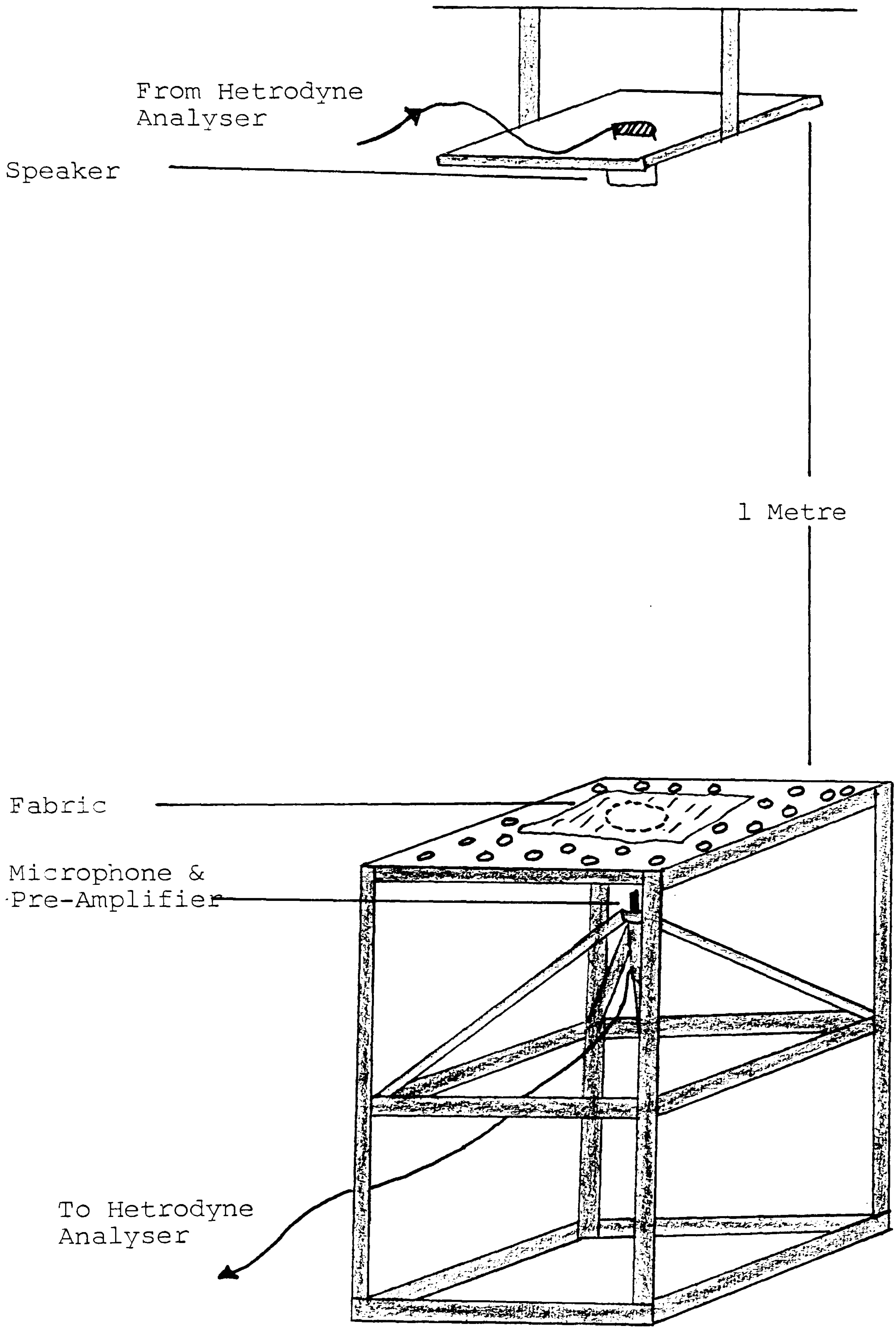
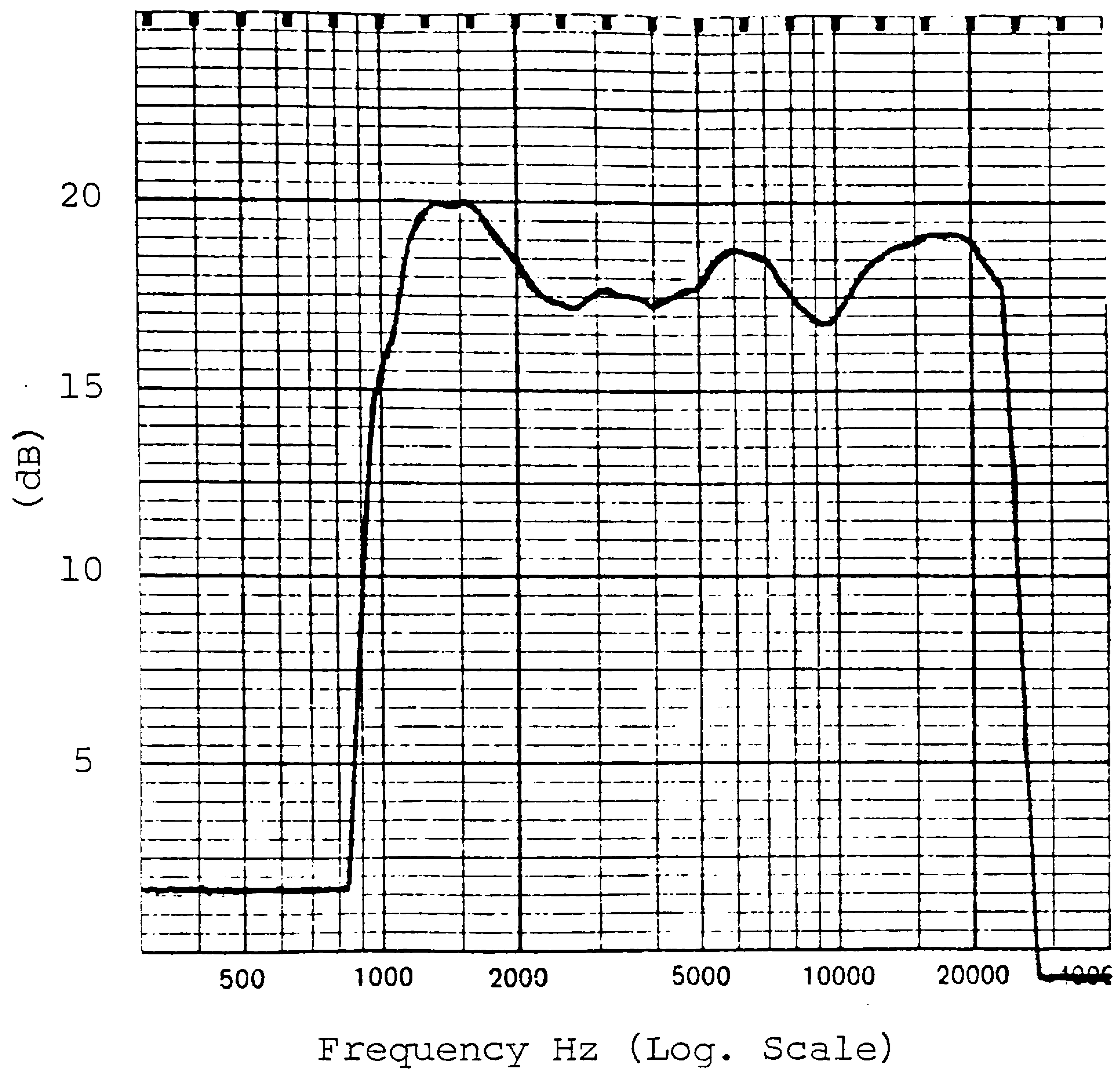


Figure 4.5 Experimental layout indicating the position of the fabric in the sound path



Figre 4.6   Frequency response of the loudspeaker

so as to give a well-defined lower limiting frequency. The frequency response of the microphone is shown in figure 4.7. The microphone is designed to operate with a DC polarisation voltage of 200 volts.

Once the appropriate microphone has been chosen an accompanying pre-amplifier must be selected. The pre-amplifier presents the the microphone with a suitable polar voltage, and has a very high input impedence and presents virtually no load to the microphone. A low input impedence enables the connecting cable between the measuring instrument and the pre-amplifier to be of considerable length. The pre-amplifier is itself powered from the frequency analyser.

For the 4113 microphone, a Bruel and Kjaer type 2619 pre-amplifier was recommended by Bruel and Kjaer. The microphone cartridge screws directly into the pre-amplifier.

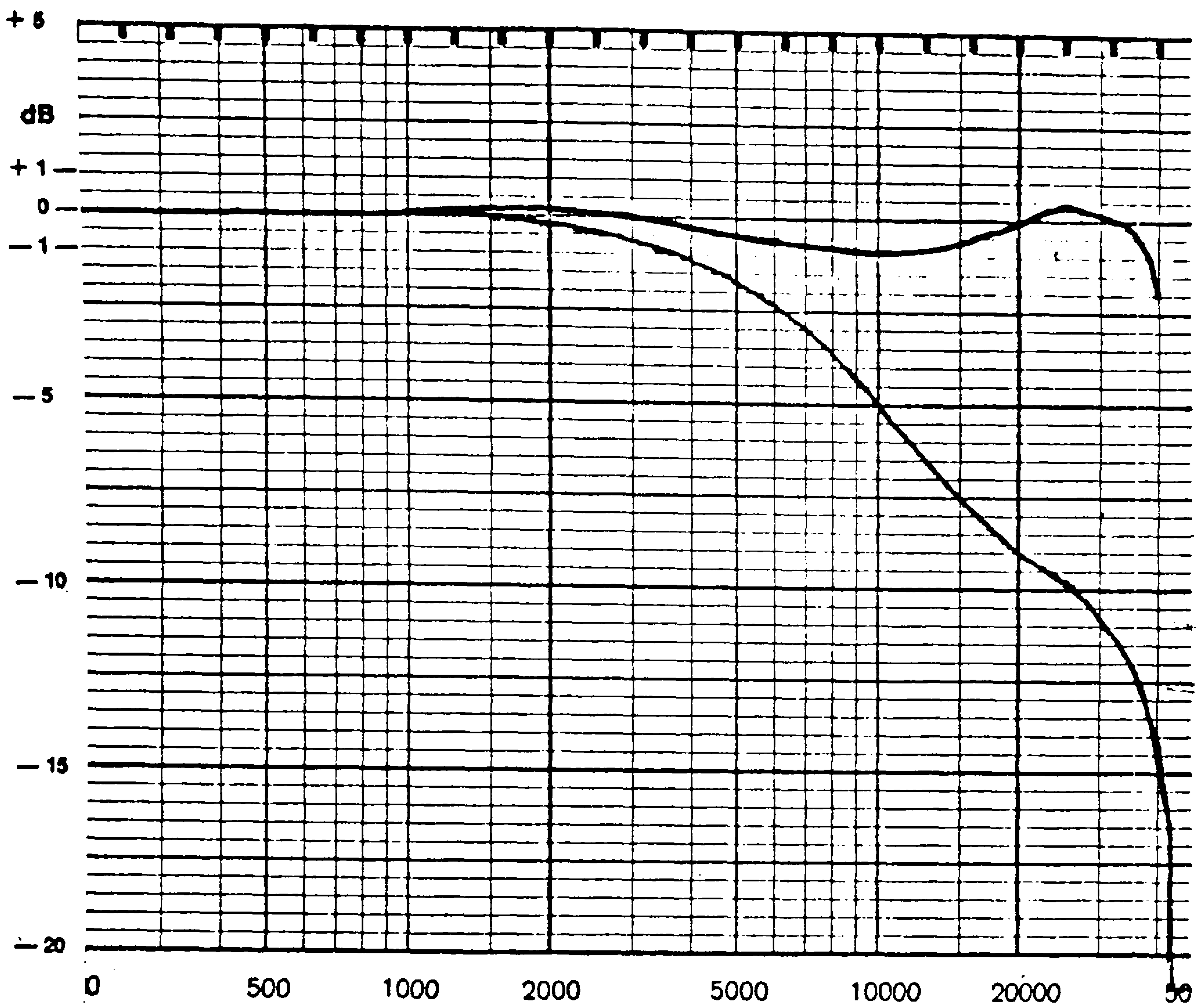
A more detailed description of these instruments may be found in the Bruel and Kjaer catalogue[100].

Recording System

The recording section of the system consists of a 'Digitrace', Marconi X-Y display unit, Bryans X-Y recorder and a Bruel and Kjaer level recorder (figure 4.8). The frequency response curves can be plotted both on the level recorder and the X-Y recorder. The individual components of the system may be discussed as follows:

The "Digitrace" made by Mr. P. Witty, School of Textile and Knitwear Technology, Leicester Polytechnic, Leicester, and designed by Mr. G. Heathaway, Rank Audio Visual, Bradford [101], is a two channel storage device in which the input information is stored in digital form. The storage form is 256 (frequency) x 8 bit amplitude. synchronisation with the rest of the equipment is achieved by a 0 to 10 volts ramp generated by the frequency analyser (2010) proportional to the swept frequency. Using the "Digitrace", a signal in one channel (B) of the "Digitrace" can be subtracted from the signal in the other channel (A) so producing an (A-B) resultant.

The Marconi Instruments X-Y display unit type



Frequency Hz (Log. Scale)

The upper curve is the open circuit free field characteristic, valid for the microphone cartridge with protecting grid and sound waves perpendicular to the diaphragm. The lower curve is the open circuit pressure response recorded with electrostatic actuator.

Figure 4.7 Frequency response of the microphone

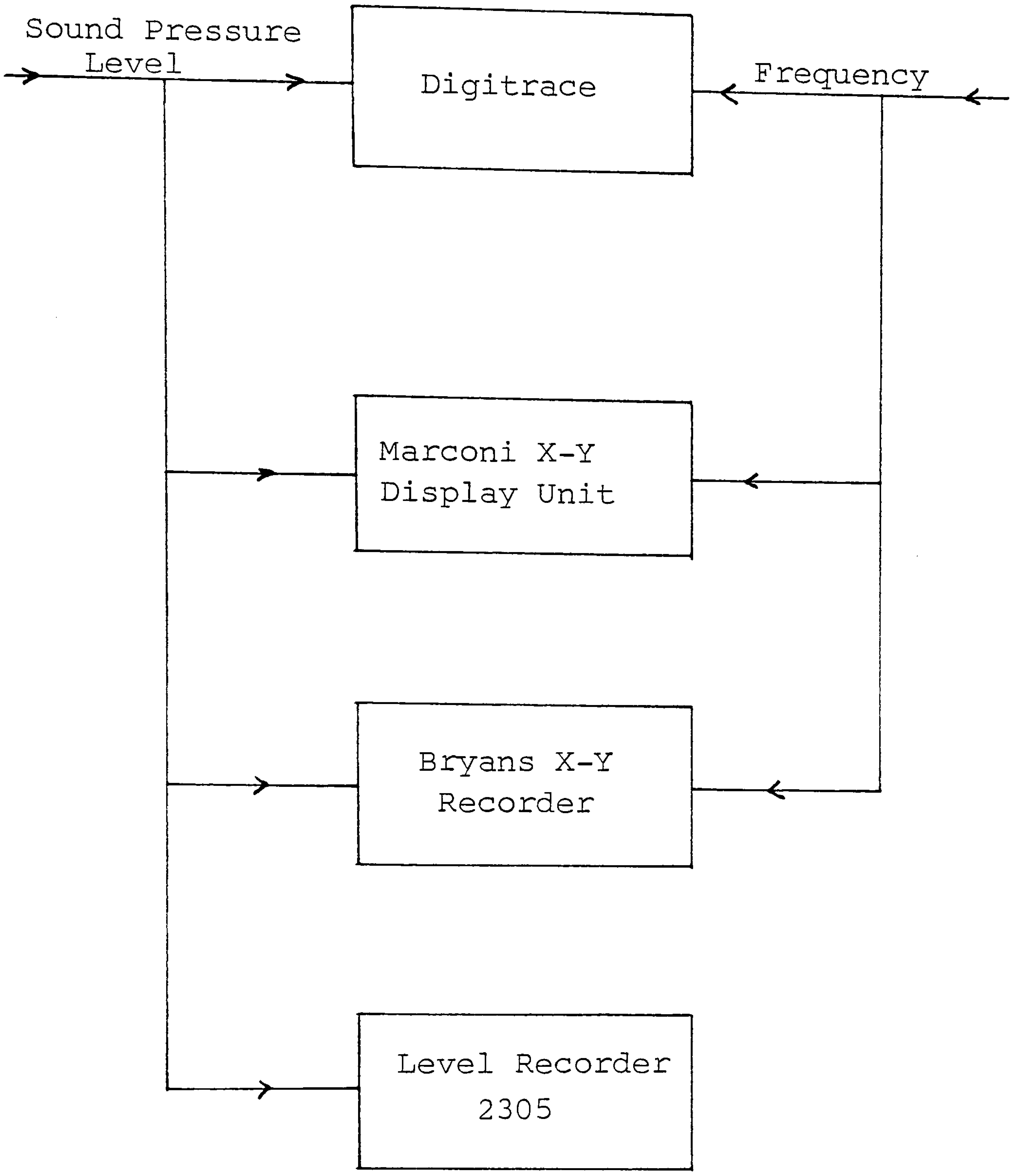


Figure 4.8 Schematic diagram of the recording system

2212A consists of an eleven inch electromagnetic deflection cathode ray tube which is used with DC coupled vertical and horizontal deflection amplifiers. The vertical deflection amplifier has a bandwidth of DC to 10kHz with a senstivity of $5mVcm^{-1}$ and the horizontal deflection amplifier has a bandwidth of DC to 1kHz with a senstivity of $100mVcm^{-1}$. A polarity switch fitted to the vertical deflection amplifier of the display unit allows an upward movement of the trace to be obtained with positive or negative input signals. The vertical axis can take a maximum input of 250 volts whereas the horizontal input can take a maximum of 350 volts. A more detailed description of this instrument may be found in the display units instruction manual(102).

The Bryans X-Y recorder type 2600 consists of a frame which accomodates A4 size graph paper. The paper is held down by a vacuum system, while paper positioning is accomplished using illuminated graticules. This instrument has an input amplifier providing senstivity from $0{\cdot}25\ mVcm^{-1}$ to $2{\cdot}5\ Vcm^{-1}$ in eight steps. Moreover the senstivity can be varied from x1 to x10 the set value, using a range control switch. There is also a pen offset which sets the pen to any position along the axis when the signal is off. Further details about this instrument may be found in the recorder units instruction manual(103).

The Bruel and Kjaer level recorder type 2305(104) is basically a recording voltmeter designed to record accurately the RMS, average or peak level of an AC signal in the frequency range 2Hz to 200kHz as well as DC signals. Recording as a function of time or frequency can be made on frequency calibrated strip chart paper. Synchronisation between the movement of the frequency calibrated paper and the frequency sweep of the sound generator is obtained with the help of a drive cable. The dynamic range of the level recorder is determined by a potentiometer which is inserted in the circuit. The input signal can be attenuated continously over the range of approximately 12dB by the input potentiometer. The resolving power of the recorder is adjustable by the potentiometer range attenuation coupled with the range potentiometer. The averaging time of the level recorder is determined by the setting of the writing speed. By combining the setting of lower limiting frequency and the writing speed, effective averaging times of the order of seconds down to approximately 10ms can be selected.

The mechanical section of the level recorder consists of a pen drive system, an event marker facility and a paper drive mechanism. As well as driving the paper, the paper drive mechanism incorporates also an automatic stop device for single chart recording and a facility for synchronisation of external instruments with paper movement. A pen-lift mechanism enables the pen to be lifted from the paper whenever desired. The pen-lift is automatic when the paper drive is in the reverse mode or switched to the "off" position. The paper drive has selectable fixed speeds ranging from 0·0003 mms^{-1} to 100 mms^{-1}. Further details may be found in the instruction manual[104].

4.4.3. Testing The Fabrics For Transmission Loss

The exact circuitory of the system employed is as shown schematically in figure 4.9. The settings of the hetrodyne analyser, level recorder and X-Y recorder are as shown in tables 4.4 to 4.6 respectively. The sound transmitted by the fabric was detected by the microphone, positioned at a fixed distance of 5mm below the fabric under test. The distance between the centre of the speaker cone and the centre of the microphone head was maintained for all tests at a distance of 1m. The fabric, the microphone, and the speaker centre were all aligned through a vertical axis.

The sequence of events involved in one fabric test was as follows. The hetrodyne analyser produced an sinusoidal wave initiated by the level recorder in the frequency range 1kHz to 20kHz to drive the loudspeaker. The wave after it passed through the fabric was detected by the microphone and returned to the analyser, where it was amplified and filtered through a variable bandwidth filter. After rectification, the signal was output to the digitrace where it was stored in digital form in memory B. Memory B was then switched to "hold" to retain this information. The fabric subsequently was removed from the sound path and a second sweep was initiated by the level recorder which was

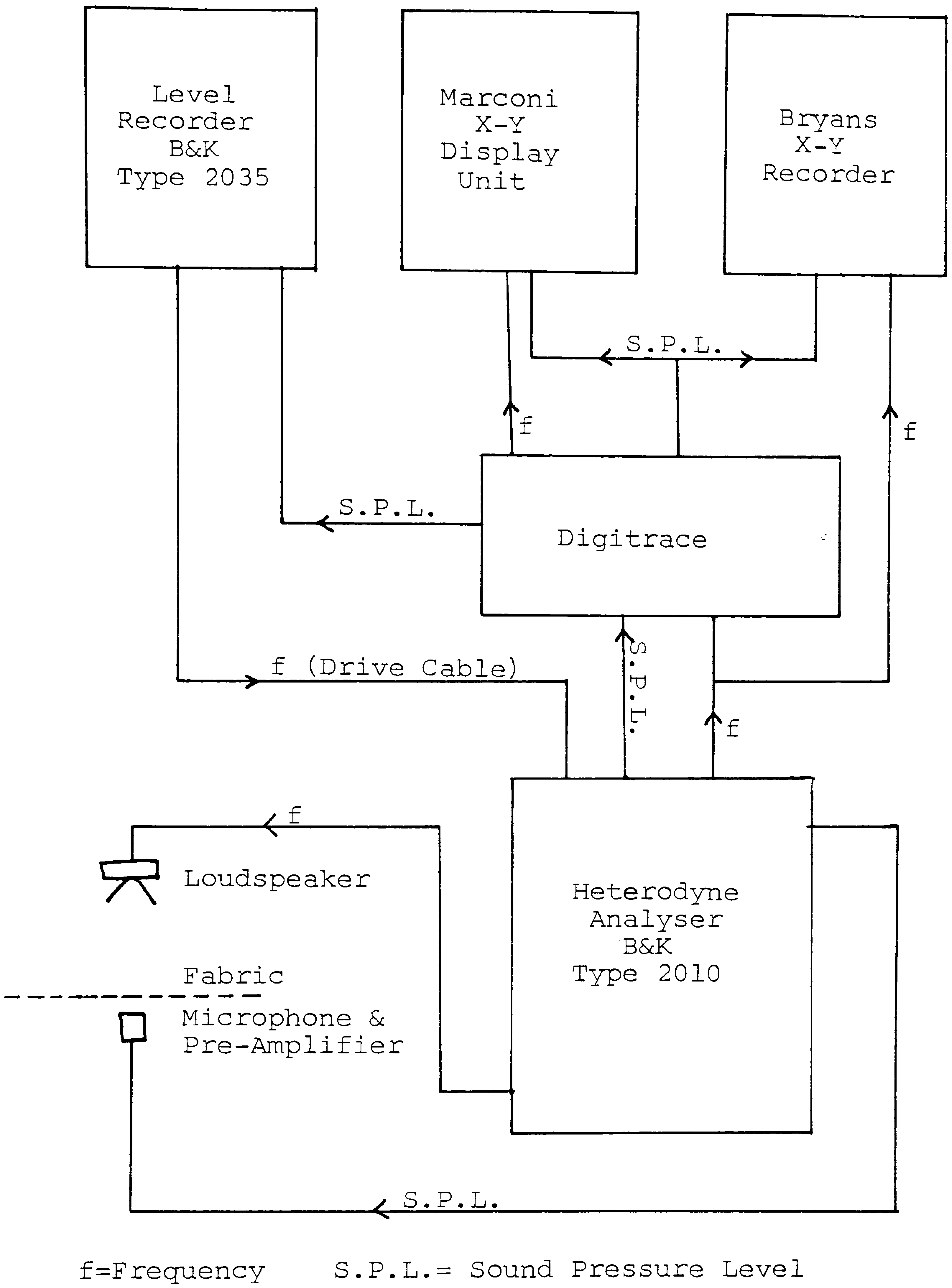


Figure 4.9 Schematic diagram of the employed acoustic measuring system

Control	Setting
Gain Control	Calibrated
Input Section Attenuator	10 mV
Output Section Attenuator	x1
Read Out Selector	Linear/Linear DC
Effective Averaging Time	0.1 sec
Input Selection	Preamp.
Calibration Function	Off
Frequency Response	Selective
Meter and Recorder Selection	Analyser
Selectivity Control	100 Hz
B&T Program	4
Frequency Scale	x1 Linear
BFO Attenuator	10 V
BFO Output Voltage	2.8
Sweep Control	Ext. Mech.

Table 4.4

Control	Setting
Potentiometer Range	16 dB
Rectifier Response	DC
Lower Limiting Frequency	10 Hz
Writing Speed	100/200 mms^{-1}
Paper Speed	100/10 mms^{-1}
Drive Shaft Speed	36
Input Potentiometer	5.2
Input Attenuator	20
Range Potentiometer	Linear Pot. Meter ZR0002 10-110 mV

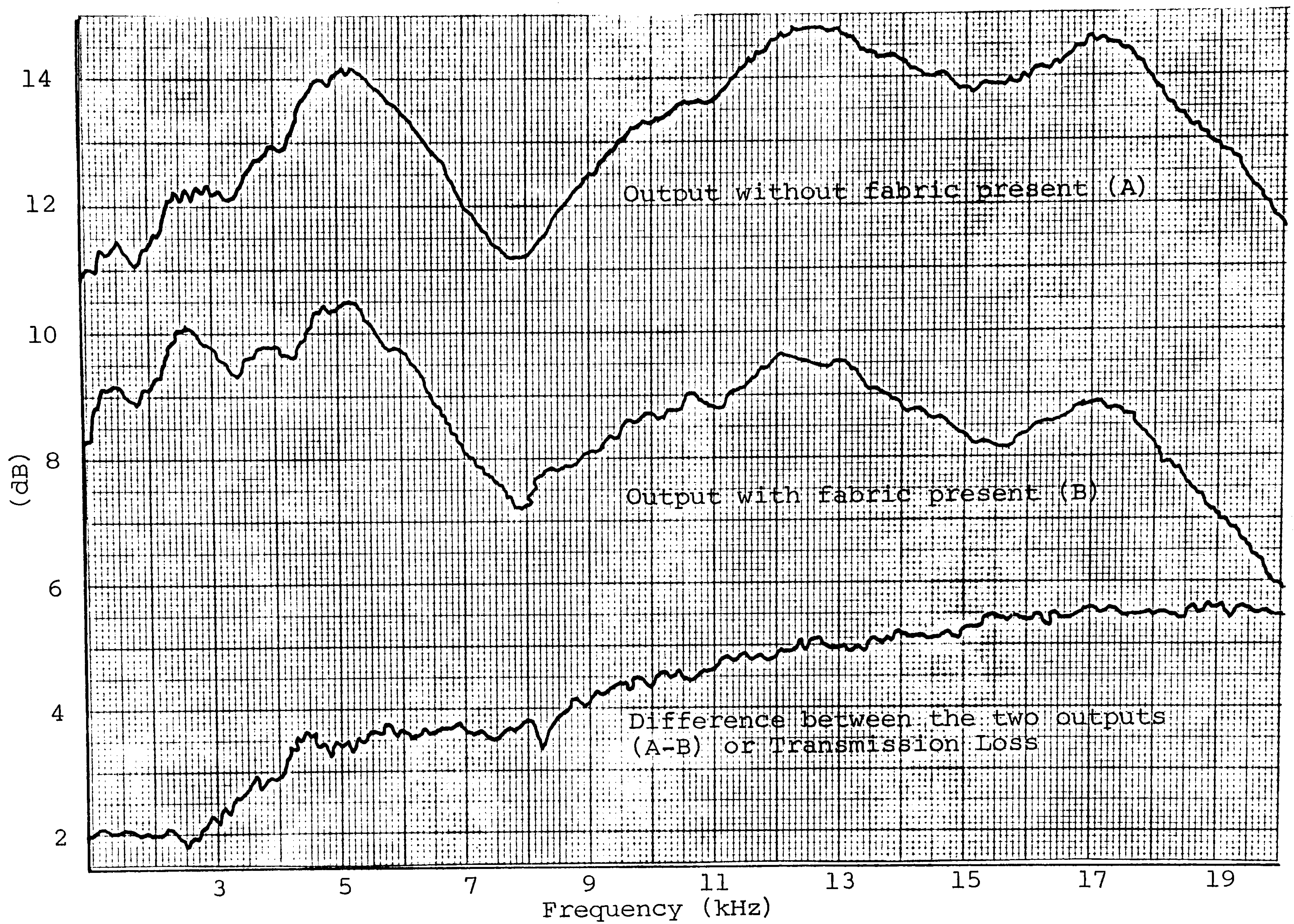
Table 4.5

Y Input Amplifier Type	26105
X Input Amplifier Type	26105
Y Input	Frequency
X Input	Sound Pressure Level (dB)
Y Input Sensitivity	0.25 Vcm^{-1}
X Input Sensitivity	25 $mVcm^{-1}$

Table 4.6

stored in memory A. With the help of the (A-B) facility, subtraction of the signal in channel B from the signal in channel A could be obtained. Consequently A or (A-B) and B could be displayed on the X-Y display unit and a hard copy of A or (A-B) could be made on the level recorder or the X-Y recorder. For each fabric the experiment was repeated on four different occasions.

Figure 4.10 shows a typical transmission loss versus frequency curve obtained from the X-Y recorder. Because of the series of peaks and troughs present in the curve, an average value of transmission loss was used rather than the actual value. For nearly all fabrics the coefficient of variation between the actual transmission loss and the average transmission loss was found to be in the range 0-3%. The average transmission loss at a given frequency (for example, 10.5kHz) was calculated as indicated in figure 4.11. The area under the transmission loss curve was calculated by counting the squares between 10.0kHz and 11.0kHz. This area then was used to construct a rectangle as in figure 4.11b, the length of this rectangle was taken to represent the transmission loss at 10.5kHz. In order not to break the continuity of the thesis the transmission loss as a function of frequency for all fabrics is listed in appendix one (table A1.1).



<u>Figure 4.10</u> Typical output from the X-Y recorder

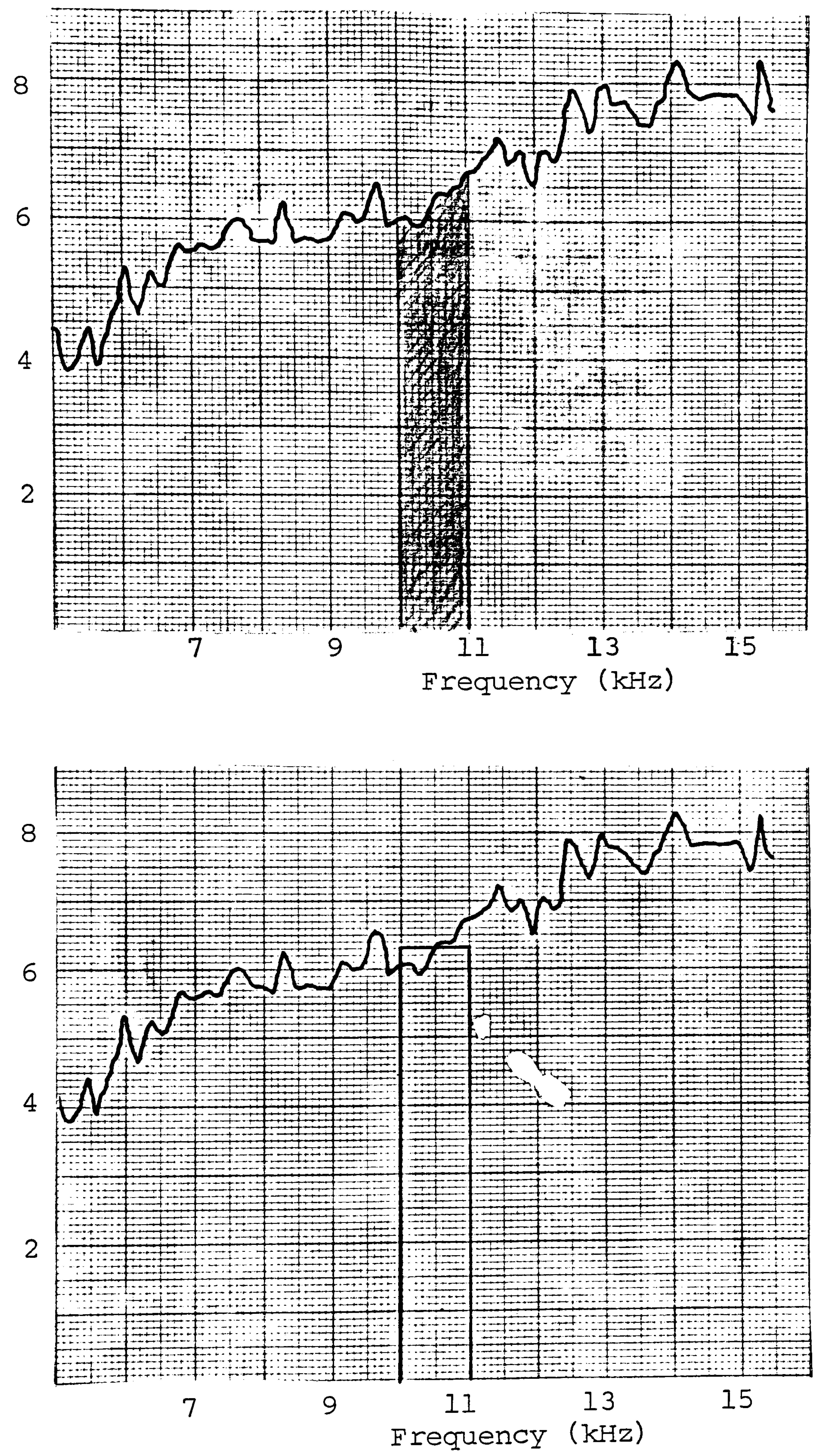


Figure 4.11 Schematic representation of the calculation of transmission loss

CHAPTER FIVE

FACTORS INFLUENCING THE AIR RESISTANCE OF NEEDLE-FELTED FABRICS

5.1 Introduction

The theory of fluid flow through porous media (such as non-woven needle-felted fabrics) has been developed largely along lines followed in the investigation of fluid flow through single tubes. For the most part the work on the flow of fluids through porous media has been an experimental verification of Darcy's law[105], which states that the rate of flow of fluid through a porous bed (v) is directly proportional to the cross-sectional area of the bed (A), and to the pressure head difference between the inlet and the outlet (Δp); and inversely proportional to the length of the bed (l), as indicated in figure 5.1 and as

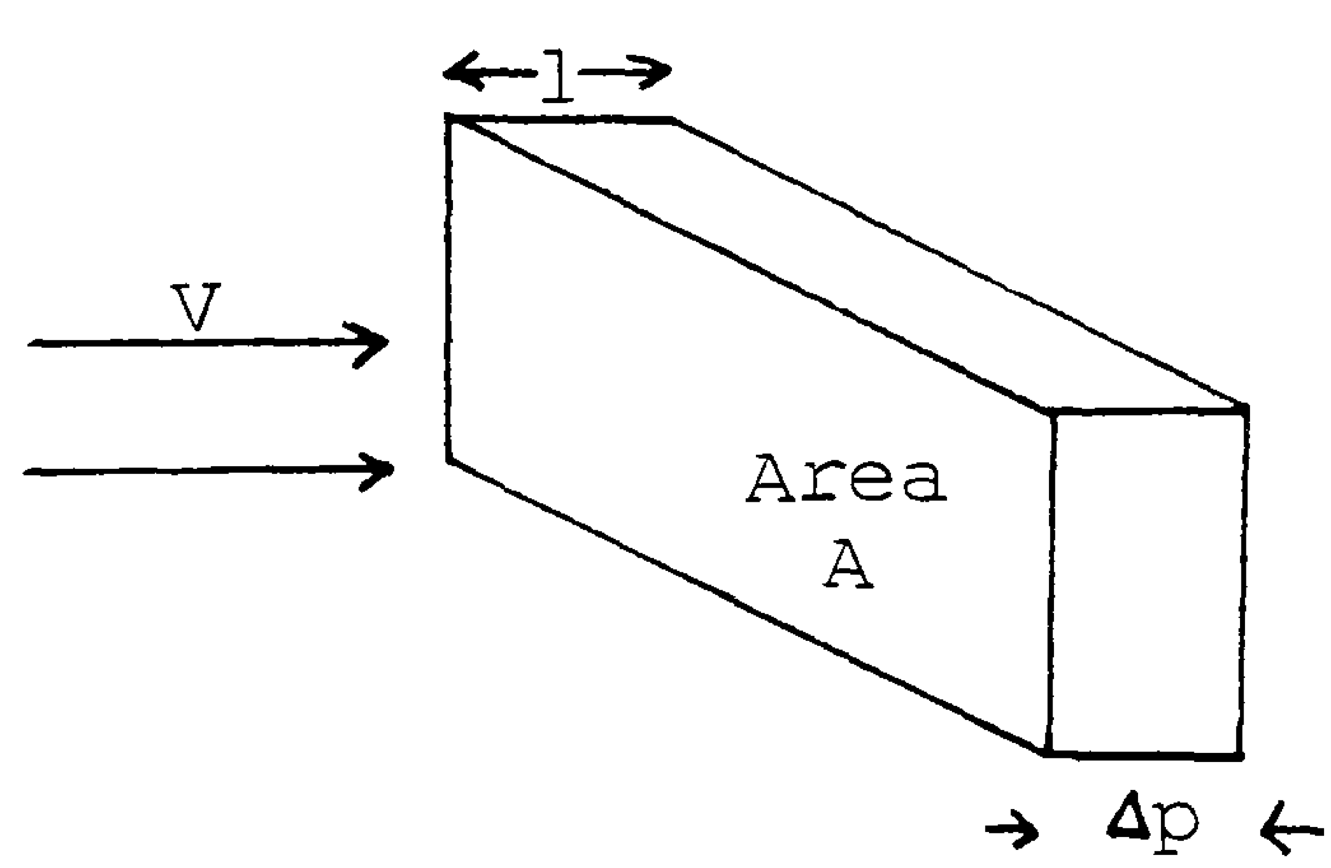


Figure 5.1 Sketch showing the flow of fluid through a porous bed.

summarized by equation:

$$v = (\text{constant})\, A\frac{\Delta p}{l}$$

The constant of proportionality must be a quantity which depends on the geometrical properties of the fabric and is the reciprocal of specific air resistance as defined earlier. The fact that the proportionality constant or the air resistance must depend on the properties of the material is obvious, since the flow resistance is the result of friction occuring between the fibres of the fabric and the air particles flowing past these fibres. Its magnitude thus would be expected to depend upon the size and the shape of the fibres, and the manner in which they are distributed and oriented in the material. The main factor that would control the air resistance would be the amount of exposed fibre surface.

The air resistance process, due to viscosity, may be enhanced to a great extent, if the fluid (air) does not travel freely, but is forced to proceed in narrow channels. Qualitatively, the reason for this is easy to understand. In narrow channels, the fluid adheres to the solid walls (fibres), and consequently large velocity gradients are set up with strong viscous forces. The resistance offered to the flow of air thus also will depend upon the distance between the fibre surfaces, and since materials can be compressed to change this distance uniformly throughout the fibre aggregation, the amount of compression thus can be varied to suit the required resistance.

The permeability of textile fabrics (which is the reciprocal of its air resistance) is a critical functional characteristic relating to many other end uses apart from sound absorption, a particular example being air filtration fabrics. The work of Kothari and Newton[106] on this subject concluded that although fabric thickness and density may be factors governing the air-permeability, their measurements indicated that the amount of material per unit area was the most important single controlling factor. However from the practical view point of the manufacturer, manipulation of the fabric weight may be impossible for many reasons such as price, weight specifications and so on. Also the work made no attempt to investigate the variation of air-permeability with fibre properties.

Clearly the air resistance of textile fabrics is a significant factor governing the acoustic properties of the material. Hence a preliminary investigation was performed to evaluate the variation of air resistance with fibre and fabric properties.

5.2 Results And Discussion

Although it was assumed in Darcy's law (equation 5.1) that the air resistance remains constant for a given material, it was noted however that for all fabrics the air resistance was velocity dependant (as displayed graphically in figure 5.2, for fabric F2), following a relationship of the form:

$$r = A + B.V \qquad \qquad ....(5.2)$$

where A and B are constants, whose values change with fibre and fabric properties.

This effect can be explained in the following manner. Generally if the flow of fluid through a fabric is steady and stable then the resistance offered to the fluid flow is due solely to viscous drag; and the work done in overcoming this resistance is expended solely in overcoming viscous drag, and this work appears as heat. If, however, the velocity of flow is too high or the air channels are non-linear (or there are other unfavourable features), a series of vortices may develop in the fluid such that the flow may become disordered or turbulent, and consequently some energy is also expended in providing kinetic energy for the vortices. Hence the air resistance will increase with the velocity of the fluid flow as a result of this turbulent flow, many published studies on air resistance show such variations of air resistance with velocity[107, 108].

Figures 5.3 and 5.4 show the variation of air resistance with fibre count and fabric weight per unit area. As can be seen, the air resistance increases with fabric weight but decreases with increasing fibre count. However, there is a considerable amount of scatter. This scatter may be attributed to the interaction effect of other fabric and fibre parameters, since in plotting these graphs, although only one parameter was selected as the independent variable, no attempt was made to keep the other parameters constant.

To examine the interaction of fabric and fibre

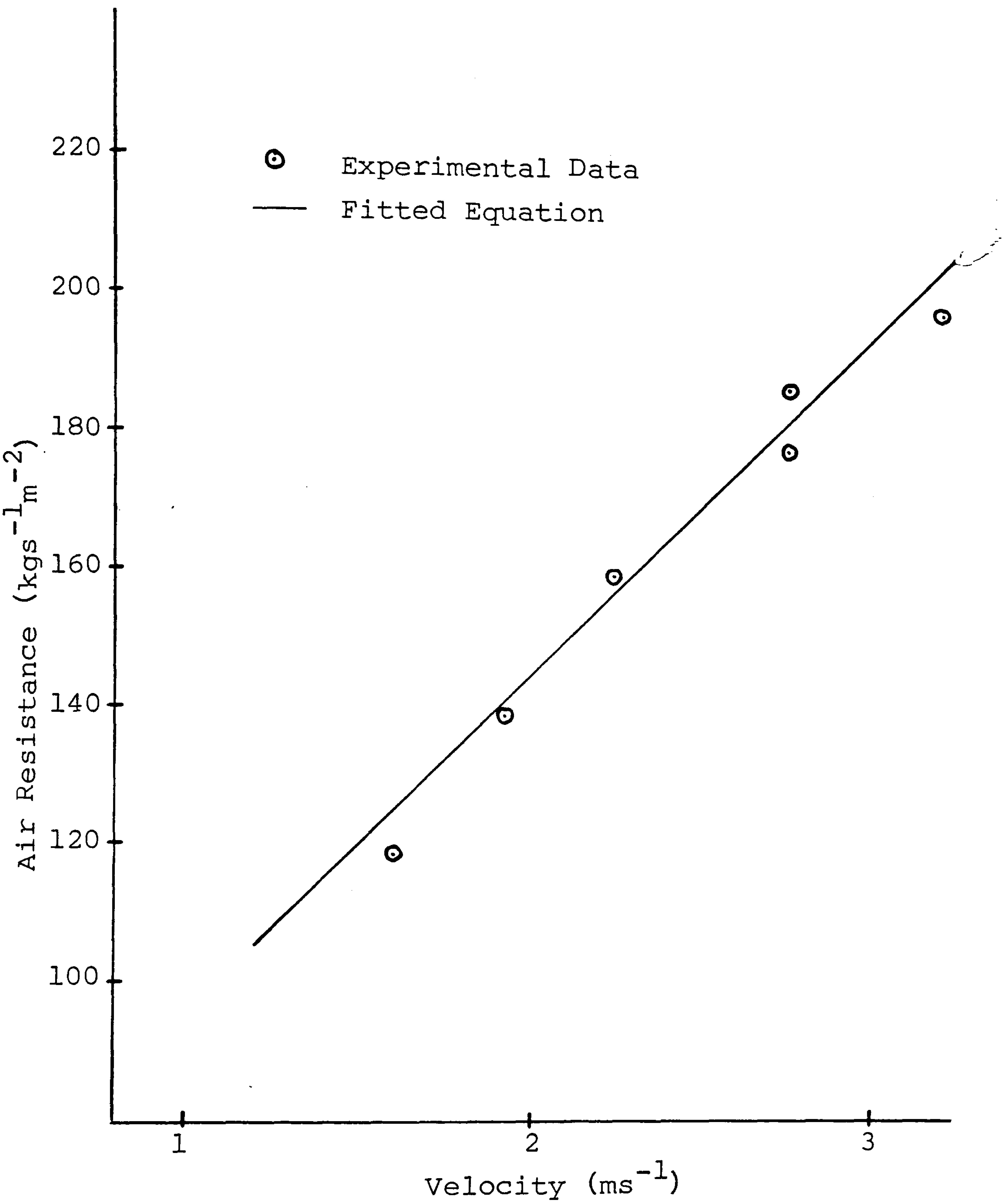


Figure 5.2 Influence of air flow velocity on air resistance.

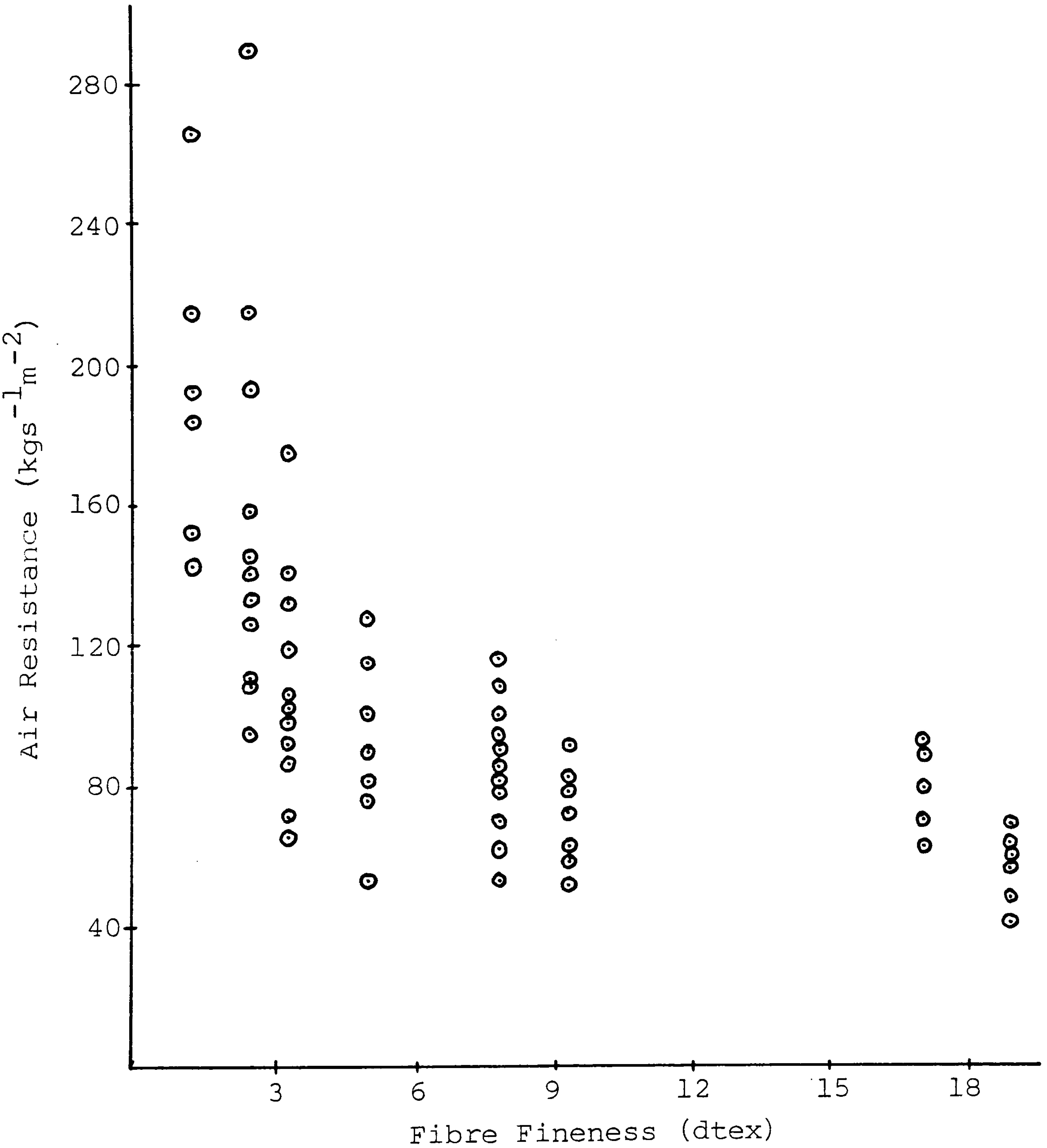


Figure 5.3 Influence of fabric fibre fineness on air resistance.

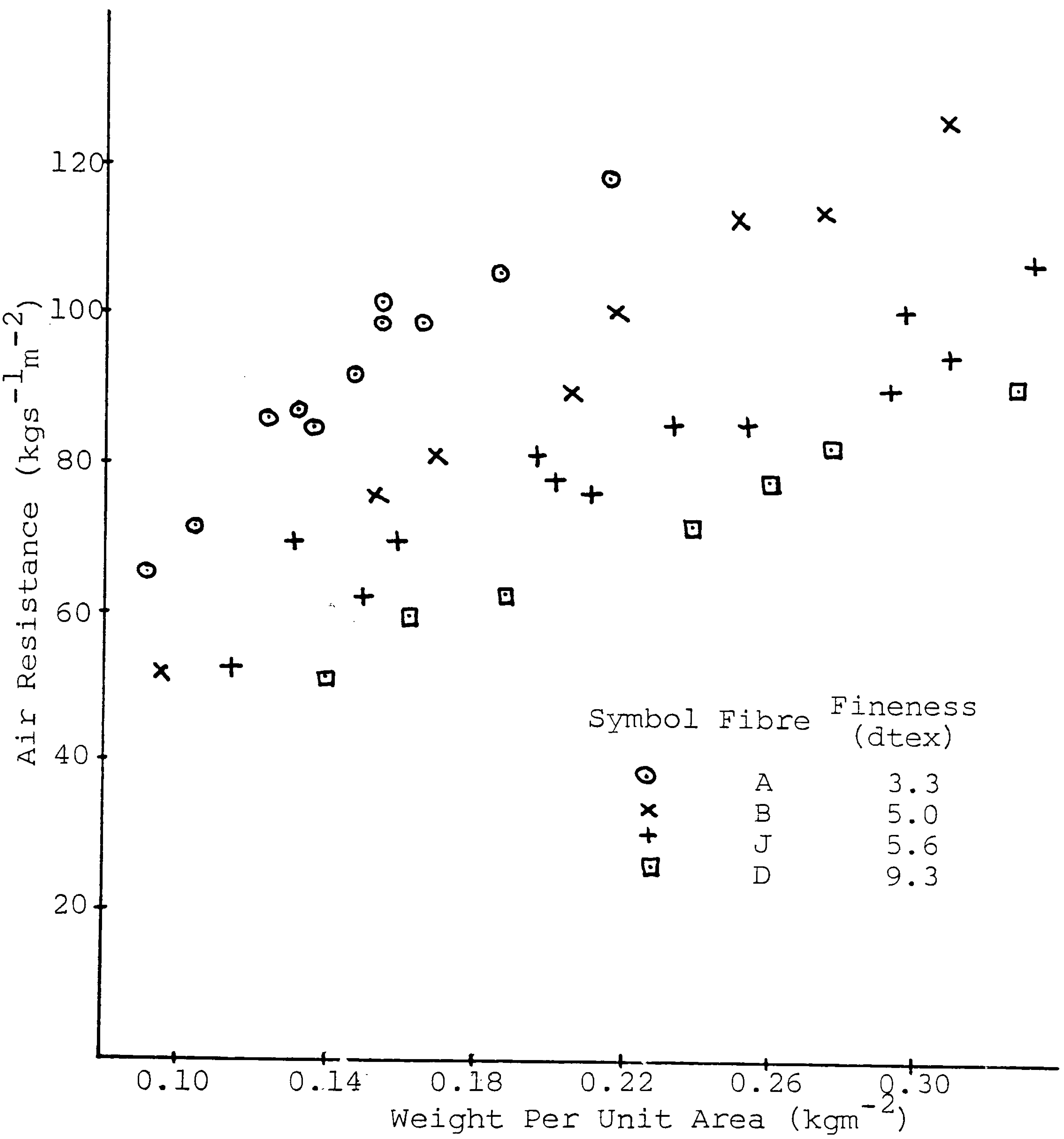


Figure 5.4 Influence of fabric weight per unit area on air resistance.

properties, an equation relating the fabric air resistance to the variables of weight per unit area, thickness, porosity and fibre count was fitted to the experimental data using stepwise multiple regression analysis[109, 110] performed by computer. The results of this analysis are listed in table 5.1. The correlation between the fitted equation and the experimental results as can be seen (0.98) is very good.

In an attempt to investigate the dependence of air resistance on the variable parameters weight per unit area and fibre count, the fitted equation was applied to a model fabric in which one parameter (weight per unit area or fibre count) was arbitarily varied while keeping other parameters constant. The results of this investigation are as discussed below.

For a given material if the thickness, weight per unit area and porosity of the needle-felted fabric are held constant and fibre count is varied, then the resistance of the fabric decreases with fibre count as indicated in figure 5.5. As can be seen considerable variation in air resistance can be achieved by varying the fibre fineness. This is as would be expected because the increase in fineness (decrease in count) increases the total number of fibres present, which in turn increases the total surface area of the fibres exposed to the flowing air. Since air resistance is as a result of friction (drag) occuring between the fibres of the fabric and the flowing air particles flowing past the fibres. It's magnitude would thus be expected to increase with the increase in the total exposed surface area of the fibres.

It is interesting to comment on the overall shape of the curves in figure 5.5, that is the initial decrease in air resistance with increasing count tending to a constant value at higher counts (above 7 dtex). Clearly this characteristic shape results since fibre count is inversely proportional to the fibre fineness and hence the number of fibres present for a given mass per unit area will also be inversely proportional to the fibre count. Because of this inversely proportional relationship the number of fibres (or the exposed surface area) present in the fabric will

Correlation Coefficient = 0.98
$r = 15.73 + 141.1\,m - 0.012\dfrac{h^3}{(1-h)^2 d} + 29034\dfrac{t}{d}$
m = weight per unit area of fabric h = porosity of the fabric d = fibre count t = thickness of fabric r = air resistance

Table 5.1

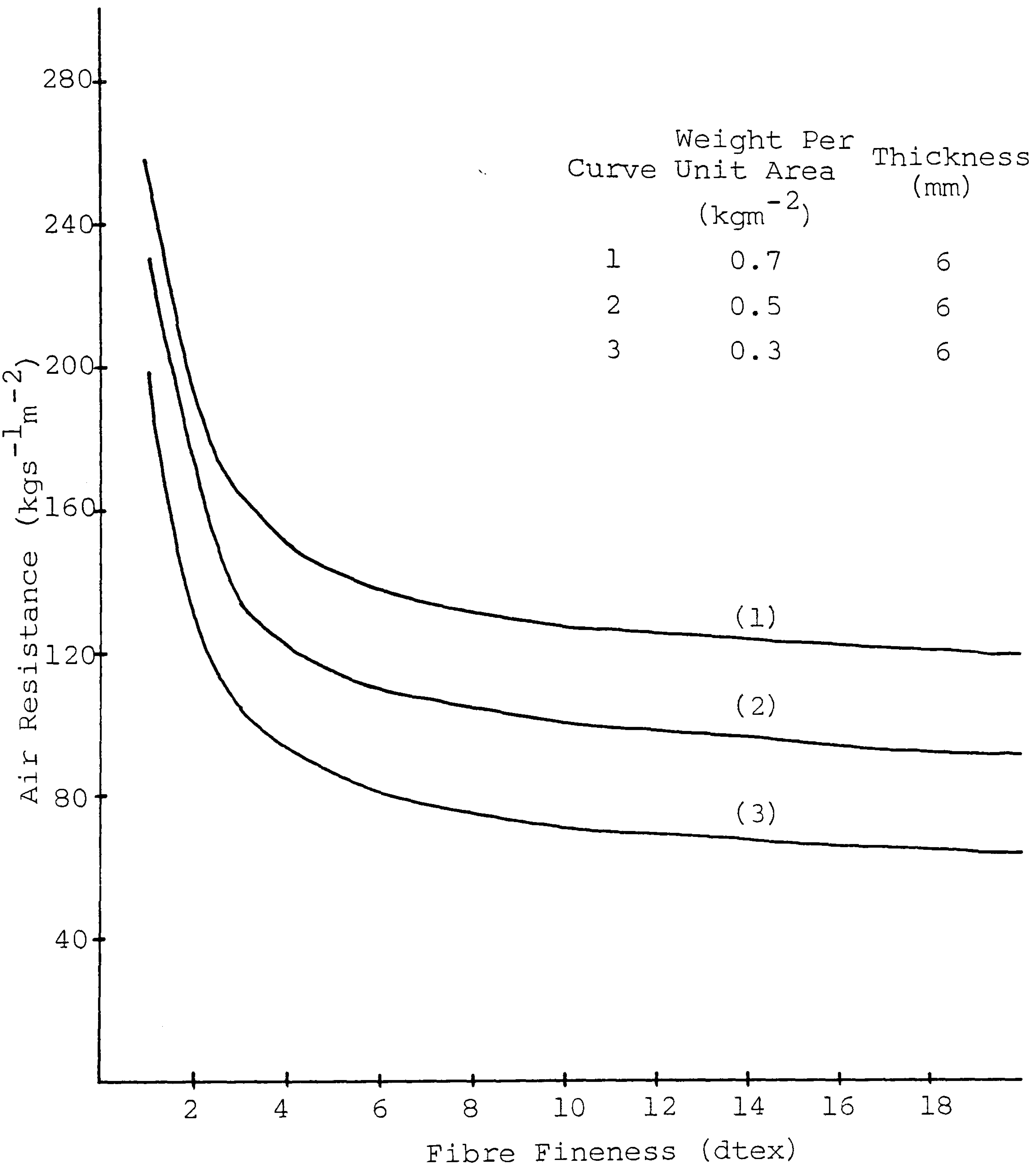


Figure 5.5 Influence of fibre fineness on air resistance.

decrease initially at a greater rate, gradually reaching a constant value.

By comparing curves (1), (2) and (3) in figure 5.5, it can be seen that for all counts, the heavier fabrics have greater air resistance. the increase in fabric weight besides increasing the number of fibres present will also increase the density of the fabric. The increase in density will decrease the diameter of the channels in the fabric, subsequently presenting higher resistance to the flow of air. Hence fabrics of higher weight per unit area will have higher air resistance due to more fibres being present and the smaller diameter of the air channels.

The effect of increasing the fabric weight per unit area on the air resistance is displayed more directly in figure 5.6, where, for a given material, the thickness and fibre fineness are held constant. In reality this situation can be achieved by packing more or less of the material in a given volume thus changing the fabric density. Hence the increase in weight per unit area not only increases the total number of fibres present but as stated previously it also decreases the size of the passages in the fabric through which the air flows. As a consequence, the air resistance will increase with the weight per unit area of the fabric, as indicated in figure 5.6. In agreement with the previous discussion the figure also indicates that for the complete range of fabric weights, a fabric made from finer fibres will have greater air resistance, and that the increase in air resistance is greater when going from fabrics made from 9dtex (curve 2) to 3dtex (curve 1) than when going from 15dtex (curve 3) to 9dtex (curve 2). This may be attributed to the inversely proportional relationship between fibre count and the total fibre surface area exposed to the flowing air, discussed previously.

5.3 Conclusion

It can be concluded that on the basis of the discussion and the experimental work a considerable amount of variation in air resistance can be achieved by

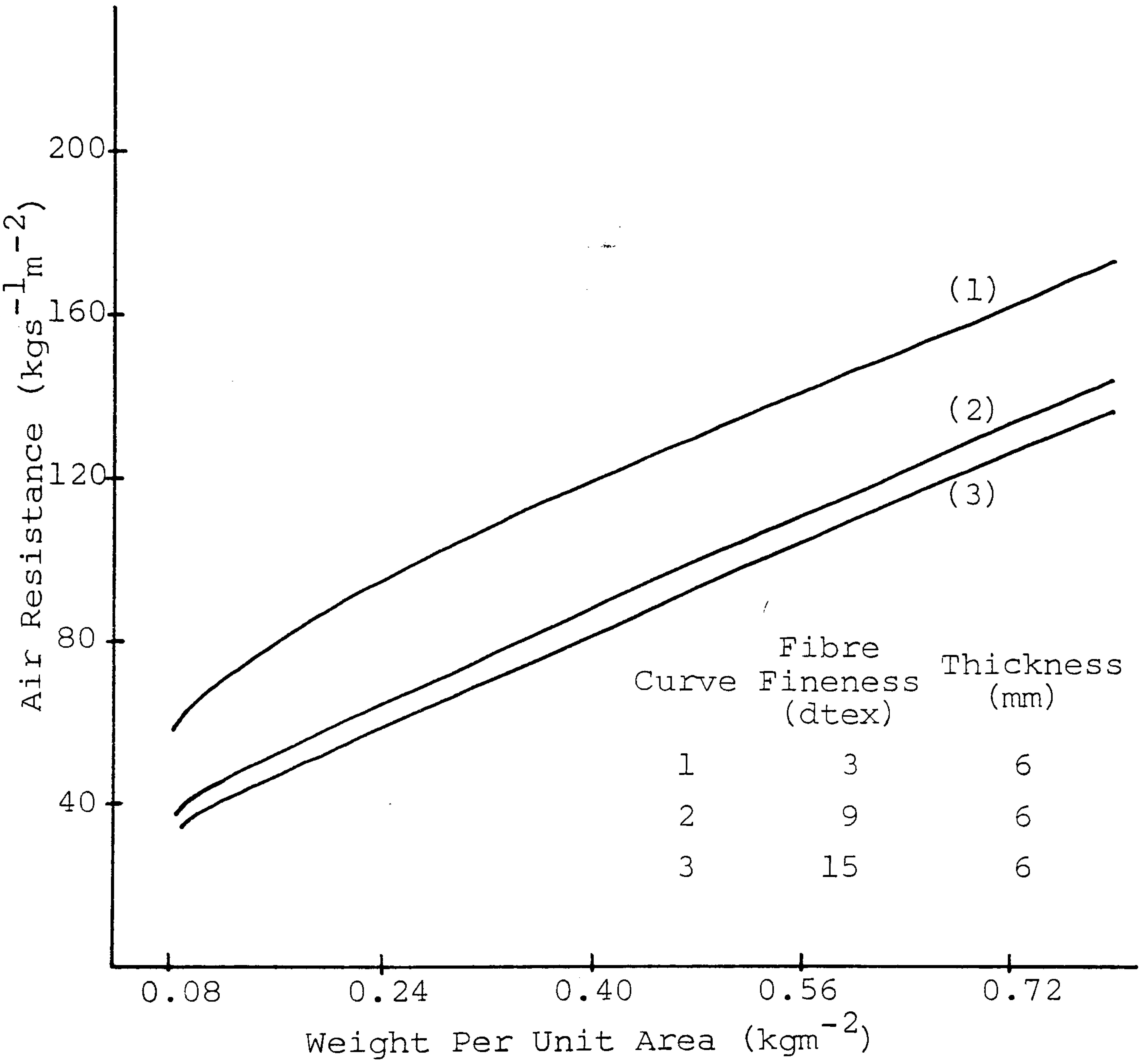


Figure 5.6 Influence of fabric weight per unit area on air resistance.

increasing the total exposed surface area of the fibres within the fabric and by decreasing the size of the channels within the fabric through which the air flows. Hence any fabric or fibre parameter which will effect these two properties will also effect the air resistance.

CHAPTER SIX

APPLICATION OF THE THEORY TO THE DETERMINATION OF ACOUSTICAL PERFORMANCE OF POROUS MATERIALS

6.1 Introduction

Porous materials such as needle-felted fabrics now are used very commonly as sound absorbing materials and a large variety of proprietary brands are available. Such materials provide the best sound absorbing characteristics in the audible frequency range. Clearly it is important that there should be adequate research performed to explain their properties and lay the basis for producing materials to be used as loudspeaker cover cloths and sound attenuating partitions. In chapter three a model of the porous material in terms of its microstructure was developed. This model then was used to predict the sound absorbed (transmission loss) by such a material from a knowledge of their weight per unit area, thickness, air resistance and porosity.

In order to substantiate the theory developed, experiments as described in chapter four were carried out on needle-felted fabrics prepared from parallel-laid webs, to determine the sound transmission loss as a result of the fabrics being present in the sound path. These experiments were carried out in the frequency range 1kHz to 20kHz.

The aim of this chapter is therefore to compare the theoretical and experimental results, examine the correlation between the two, and make an attempt to explain any discrepancies.

6.2 Comparison Of Theoretical And Experimental Results

The experimentally measured and theoretically predicted transmission loss versus frequency characteristics are shown in figures 6.1-6.4, for a selection of fabrics. Produced for comparison purposes, the experimental and the theoretical results are plotted on the same graph.

As expected the transmission loss was found to increase with the frequency of the sound source, because of increasing inertia and resistance forces, due to the fact

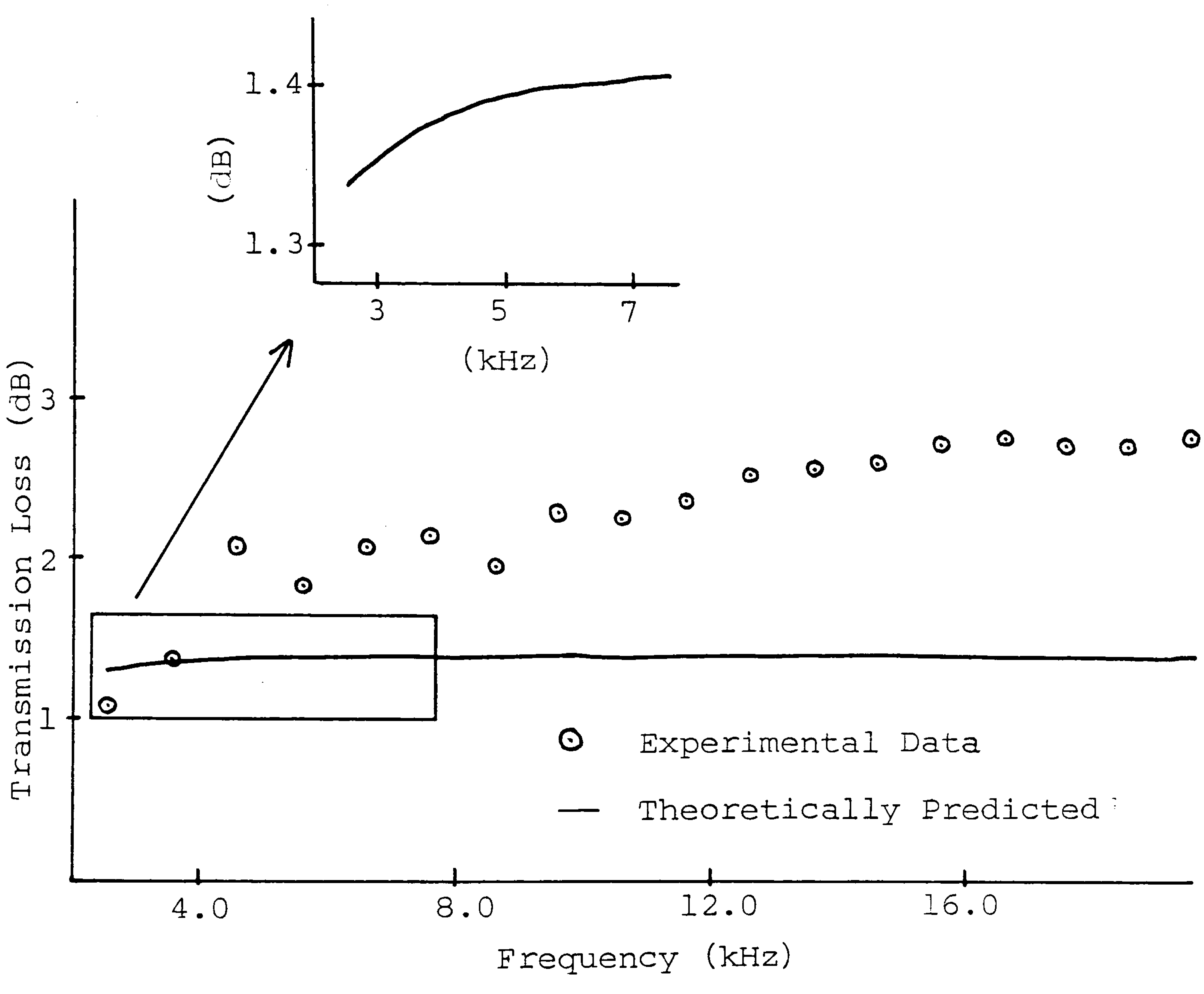


Figure 6.1 Experimentally measured and theoretically predicted transmission loss versus frequency characteristics for fabric A5.

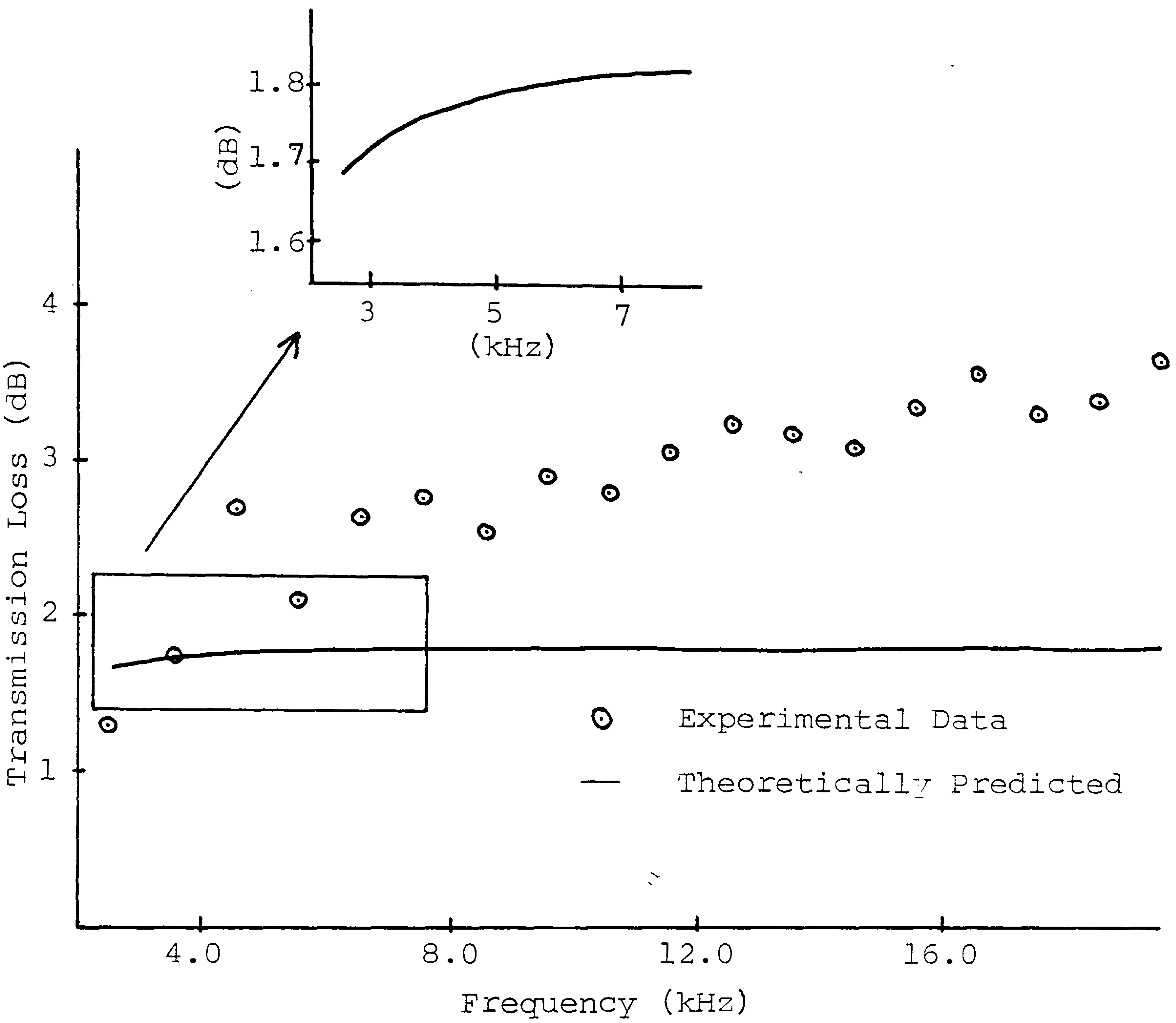


Figure 6.2 Experimentally measured and theoretically predicted transmission loss versus frequency characteristics for fabric G4.

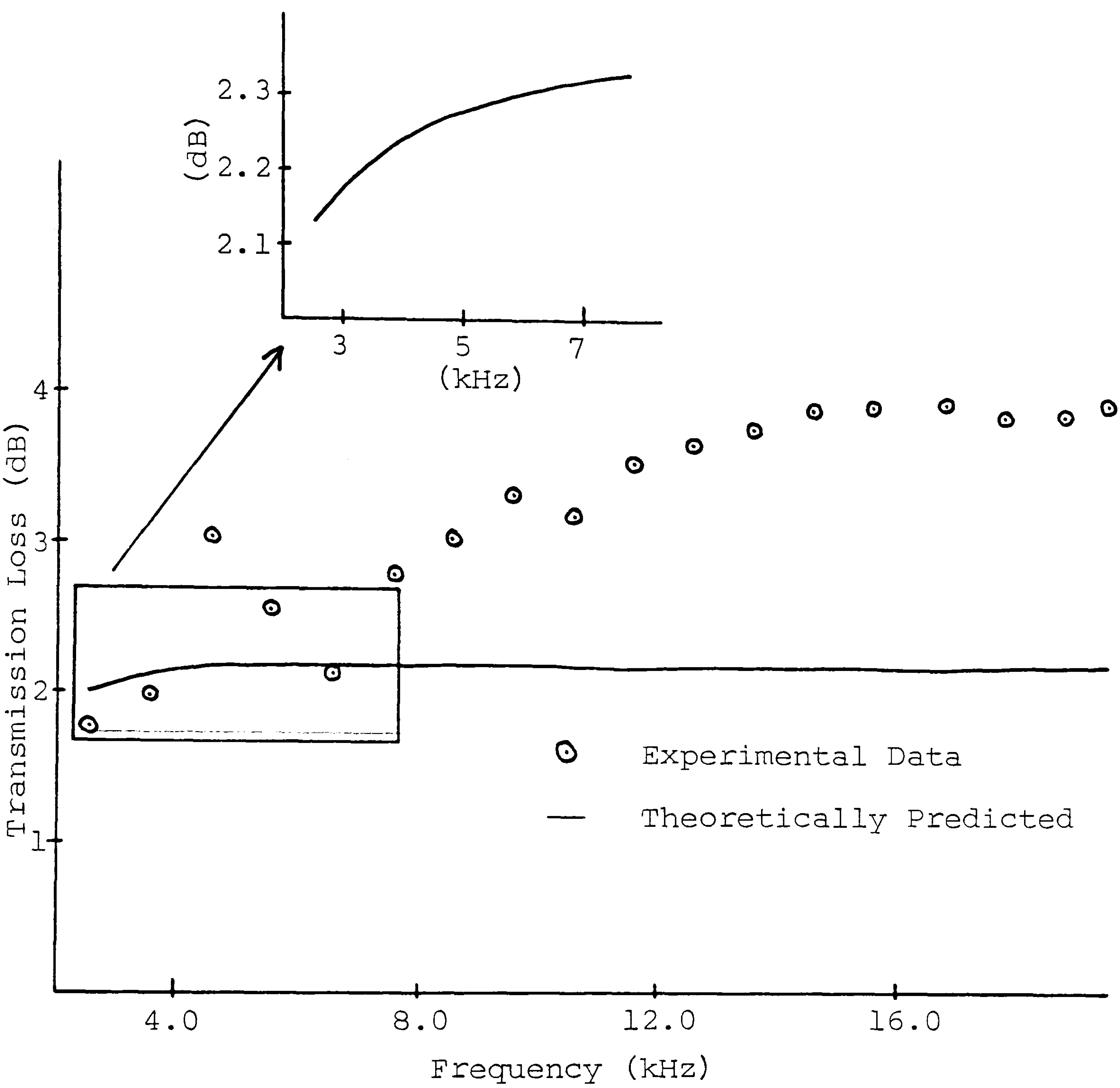


Figure 6.3 Experimentally measured and theoretically predicted transmission loss versus frequency characteristics for fabric B8.

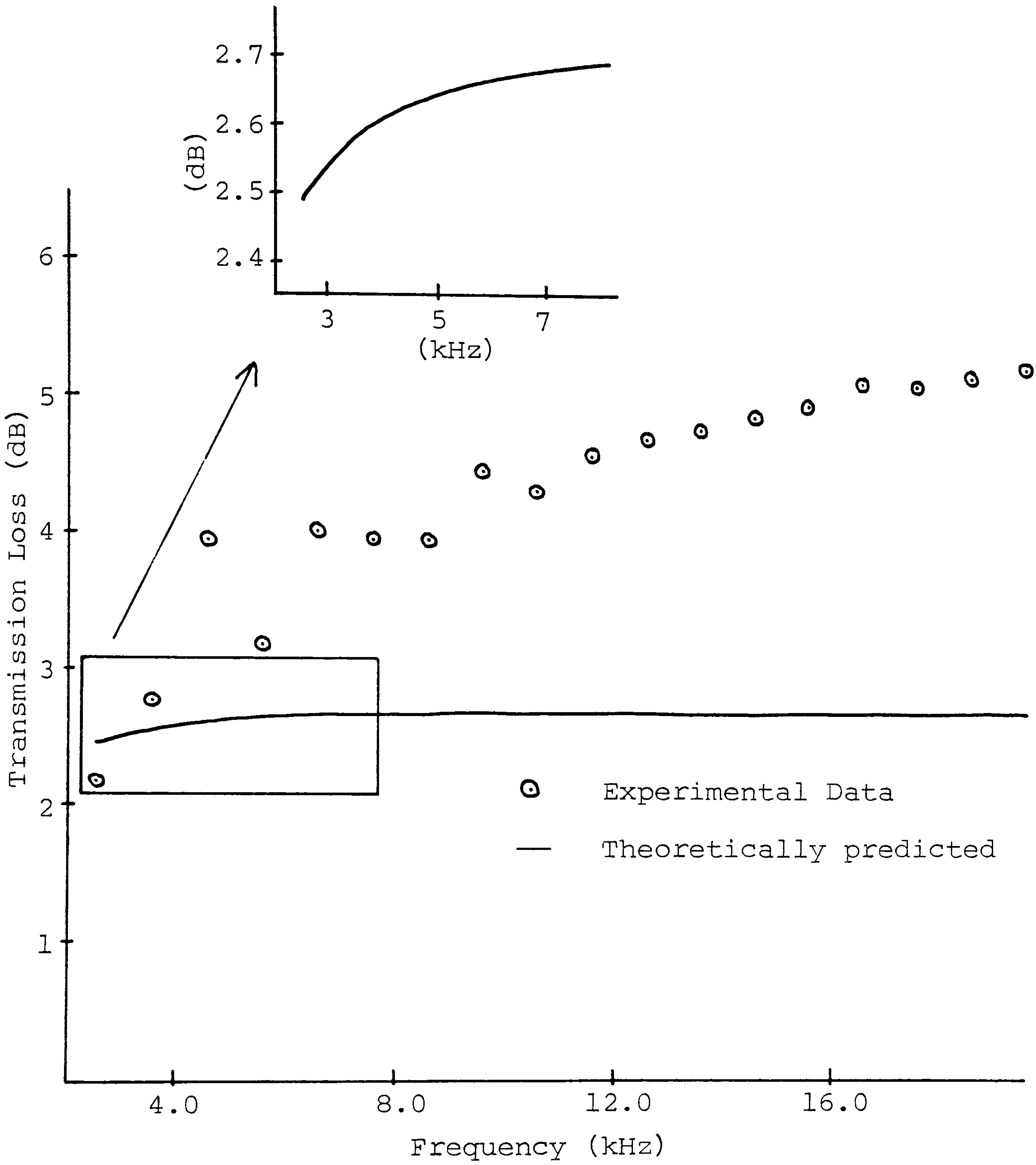


Figure 6.4 Experimentally measured and theoretically predicted transmission loss versus frequency characteristics for fabric G7.

that a given air particle in the sound wave will be vibrating to and fro more times per second and so will experience a greater resistance to its motion. Both experimental and theoretical plots of transmission loss versus frequency (figures 6.1 to 6.4) confirm this. The theoretically predicted results are computed from equation developed in chapter three, namely:

$$\text{Transmission Loss} = 8.69.\Delta x.\alpha \qquad \text{.......(6.1)}$$

where Δx is the thickness of the fabric and α is the attenuating constant. The theoretically predicted transmission loss versus frequency characteristics for the fabric model developed in chapter three have the same general shape as for the experimentally measured results, in that initially the rate of increase of transmission loss with frequency is much greater but decreases at higher frequencies. However it can be seen that considerable differences in the theoretically predicted and experimentally measured results exist especially at high frequencies. At low frequencies the fit seems to be fair.

6.3 Discussion

Considering the simplicity of the theory developed and the assumptions made, some discrepancy between the theoretical and experimental results would be expected. Before a detailed analysis of the results, it is necessary therefore to attempt to explain these differences in terms of experimental and theoretical factors.

Most of the needle-felted fabrics used in the present work were quite uniform as an effort was made to distribute the fibres evenly during fabric production so that bunching of denser units did not occur, and average constant were determined from static measurements made on the samples. Attempts also were made to reproduce fabric mounting conditions in the sound path. Hence experimental error due to these two factors cannot be the cause of the observed discrepancies mentioned above.

For the theoretical model developed in chapter three, it was assumed that in the body of the fabric, the fibres are arranged in such a way that the medium consists of straight narrow channels of constant cross-sectional area running parallel to the direction of the sound wave. Clearly a needle felted fabric will contain these channels but they will not be as idealised as assumed. However it is unlikely that this simplification could be the cause of discrepancy between the experimental and theoretical results since it would not be expected to introduce a frequency dependence. Evidently, it is this frequency dependence that may be a significant factor. On plotting a graph of experimentally measured transmission loss minus theoretically predicted transmission loss as a function of frequency (figure 6.5), it can be seen that the difference between the measured transmission loss and theoretically predicted transmission loss is highly frequency dependent, especially at high frequencies indicating that either the theory lacks in some respect or that one of the fabric variables is perhaps frequency dependent. Since all fabric constants (thickness, weight per unit area, air resistance, porosity and fibre density) were measured at zero frequency, a frequency dependence by one of these fabric constants could be the cause of the observed discrepancies. Clearly fabric thickness, fabric weight per unit area and fibre density cannot be frequency dependent and neither will be the fabric porosity since it is calculated from the fabric thickness, weight per unit area and fibre density.

However, it is likely that air resistance is frequency dependent and infact this variation has been reported by other workers[111, 112]. There are three arguments that may be proposed to explain this dependence and as such they are itemised below:

<u>Argument One</u>

The structure of the porous material is very complex in that the passages in the medium through which the fluid moves in general have irregular cross-sections. For instance some pores or channels in the material will have somewhat isolated positions (may be partly sealed off) such that the air content of these pores will not move during a normal air resistance experiment as described

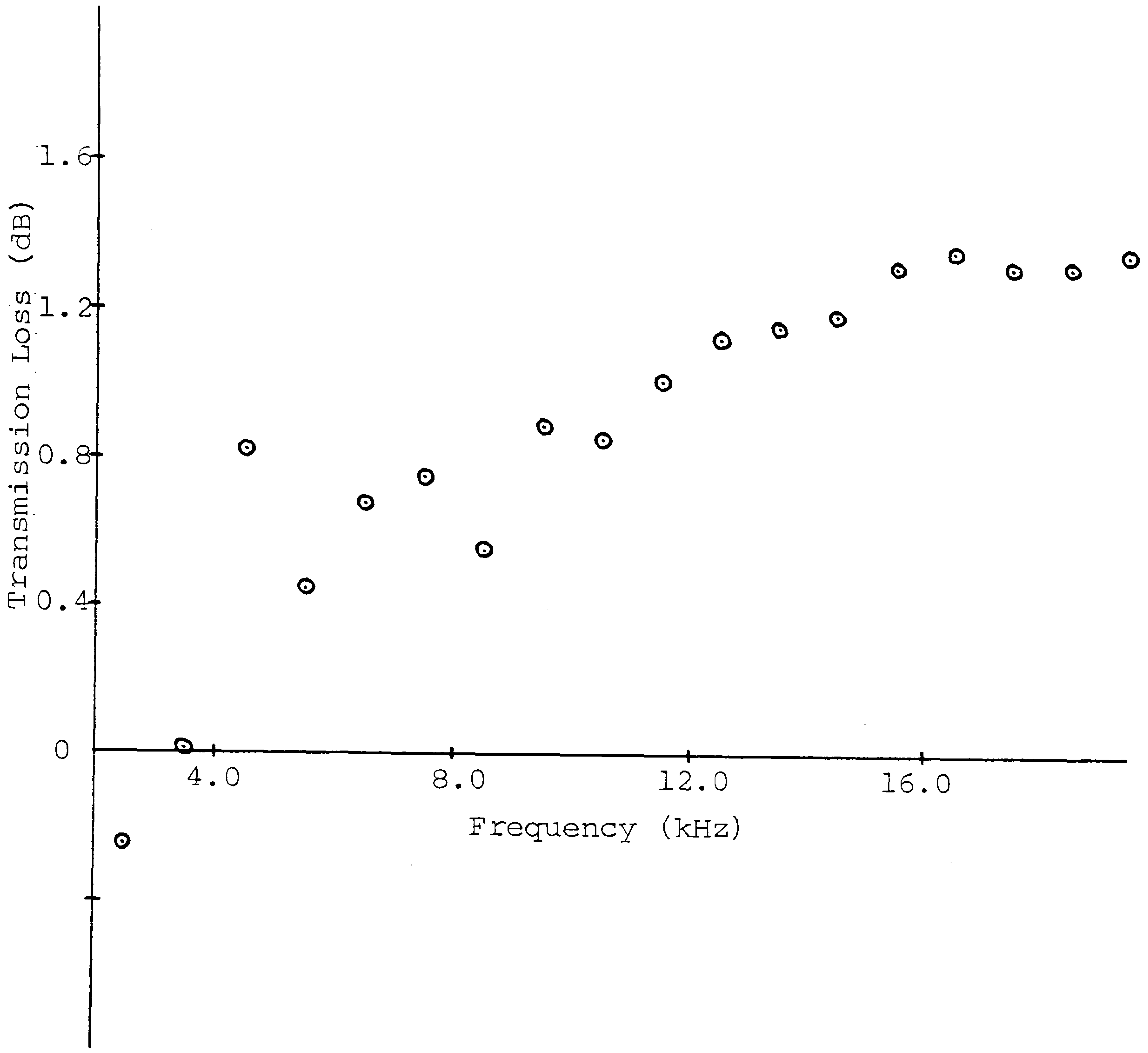


Figure 6.5 Experimentally measured transmission loss minus theoretically predicted transmission loss versus frequency for fabric A5.

in chapter four. However these "remote" pores may come into action when the frequency is not zero, since in this case the pressure in all the pores has to vary owing to the travelling wave. Air resistance is a result of "drag" experienced by the flow of fluids past solid surfaces and the increase in exposed area of such solid surfaces thus will increase the air resistance. With increasing frequency, more of these pores will come into action, until a point is is reached when no more are available. Clearly this approach quite elegantly would explain the frequency dependence of air resistance. Moreover, it suggests a mechanism by which a stable structure would be achieved beyond a certain frequency, thus explaining the tendency towards a constant value of (measured transmission loss minus theoretically calculated transmission loss) displayed in figure 6.5.

Argument Two

It may be that the phenomena associated with the properties of microscopic fluid channels play an important part in the behaviour of fabrics when tested under low and high frequencies. Consider the flow of a liquid in a cylindrical tube of radius (a) and length (l), with different pressures (p_1) and (p_2) maintained at the ends of the tube. For such a case, the fluid flows along the tube under the action of the pressure difference:

$$\Delta p = p_2 - p_1$$

The flowing fluid will have what is called a parabolic velocity profile, that is, the velocity varies as shown in figure 6.6 from zero at the wall, to a maximum value at the axis of the channels. The maximum value of velocity obviously will depend on the radius (a), length (l) and pressure difference(Δp)[113].

Consider the fluid flowing, as stated to be divided into parallel strata in such a manner that while each stratum moves in its own plane with uniform velocity, a change in velocity occurs in passing from one stratum to another. Under these circumstances a tangential force between contiguous strata given by:

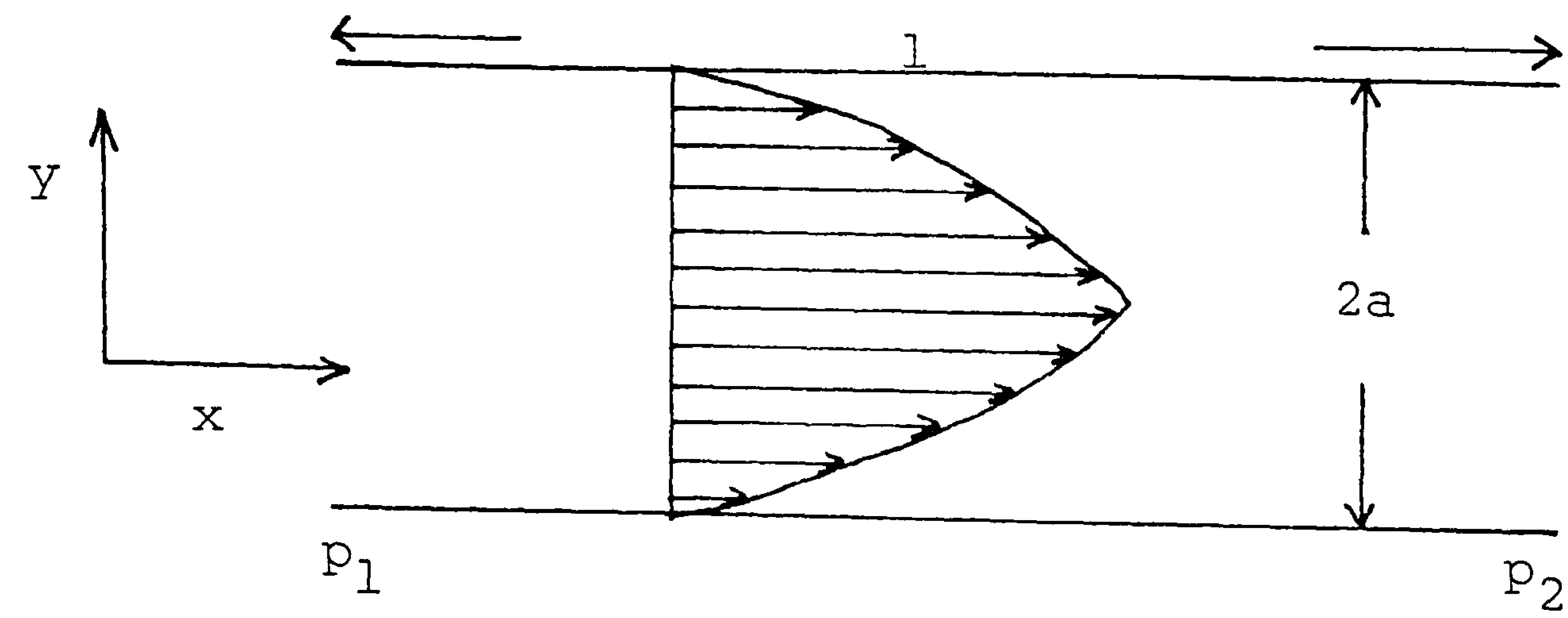


Figure 6.6 Sketch showing the parabolic velocity profile of a flowing fluid.

$$\text{Tangential Force} = \eta \frac{dv}{dy}$$

where η is the viscosity of the fluid and $(\frac{dv}{dy})$ is the velocity gradient across the radius of the tube, comes into play. Thus the effective value of the air resistance will depend on the distribution of velocity across the channel $(\frac{dv}{dy})$.

As the frequency increases, the velocity field will gradually change to a flow profile where the effect of viscosity is confined only to a thin boundary layer in the vicinity of the rigid walls (fibres). Since there is insufficient time for the air strata to develop the parabolic velocity profile as in figure 6.6. At the surface of the wall there will be no relative motion between the fluid and the wall. For positions well away from the wall surface, the velocity will tend to a uniform value. The velocity over the intervening section will depend on the frequency. At frequencies above zero the velocity gradient will tend to be concentrated near the surface of the wall in a boundary layer whose thickness as indicated in figure 6.7, decreases as frequency increases. As a

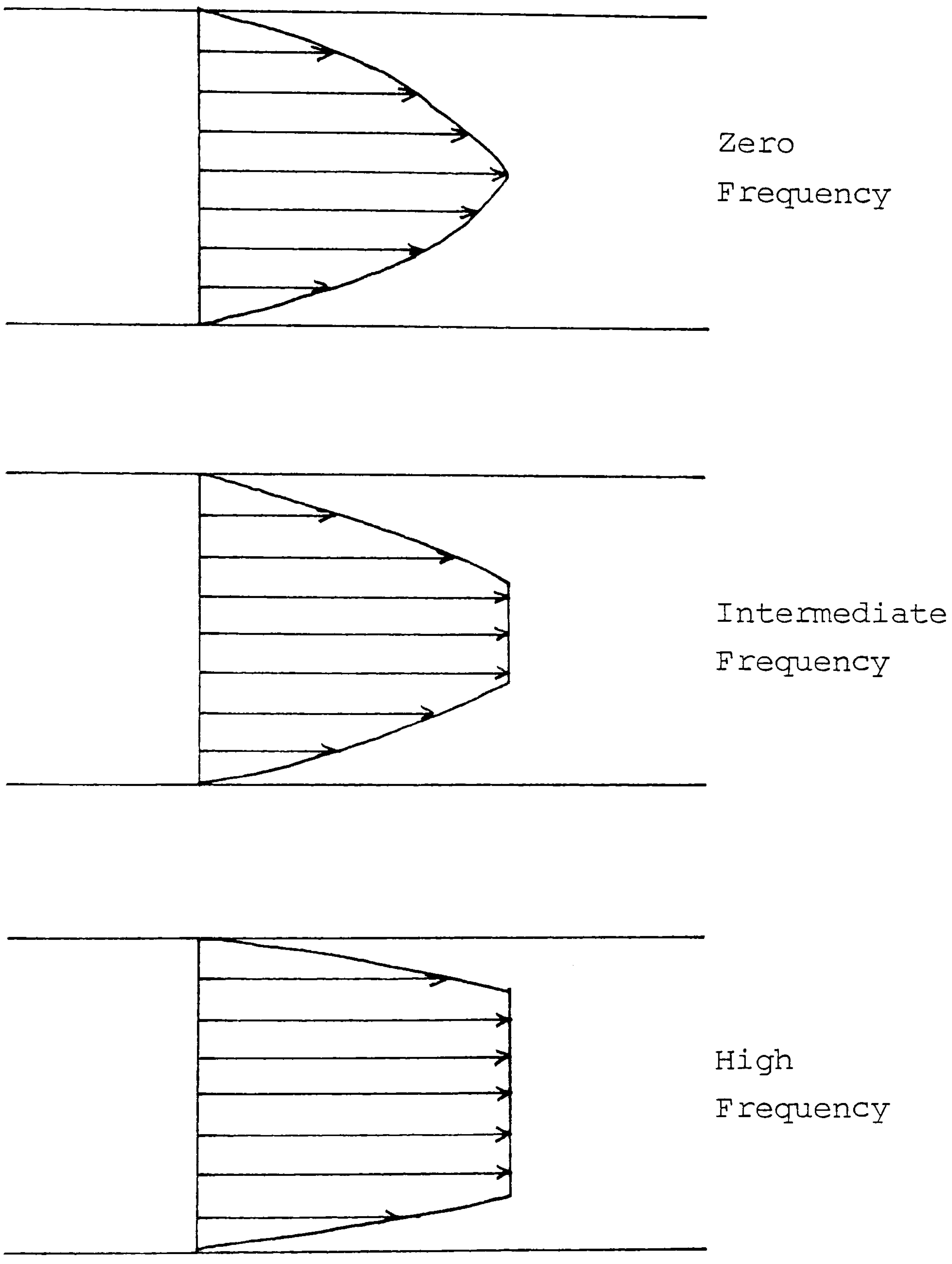


Figure 6.7 Sketch showing the suggested variation of the velocity profile.

consequence of decreasing (dy), as indicated in equation 6.2, the magnitude of air resistance (tangential force) will increase with frequency. Biot[114] suggests that the thickness of the boundary layer will decrease as $(\text{frequency})^{\frac{1}{2}}$, hence the air resistance, as a consequence will increase as $(\text{frequency})^{\frac{1}{2}}$.

Argument Three

The third possibility for the variation of air resistance with frequency is a consequence of the fact (discussed in the last chapter) that air resistance (r) is velocity dependent, following a relationship of the form:

$$r = A + BV$$

where A and B are constants and V is the velocity of flow. The magnitude of A and B depend on fabric properties. Work by other workers[112, 114, 115] suggests that the velocity of propagation of sound in porous materials is not constant but depends on the frequency of the sound source. The work of Kawasami[115] suggests that sound velocity is very small in the low frequency range. But between the low and high frequency range region it is proportional to $(\text{frequency})^{\frac{1}{2}}$ and approaches the velocity in air in the high frequency range. Hence air resistance will also be frequency dependent.

The stated arguments suggest that for a given fabric the air resistance is not constant but increases with frequency. No method is available for directly measuring air resistance as a function of frequency. However, by measuring all other parameters including transmission loss, air resistance at a given frequency can be computed indirectly using the theoretically developed equation:

$$\text{transmission loss} = 8.69.\Delta x.\alpha \qquad \ldots\ldots.(6.1)$$

where as mentioned earlier:

Δx = thickness of the fabric

$$\alpha = \text{attenuating constant} = \left[\frac{wkh}{2p_o}\left\{-Y_i + (Y_i^2 + Y_r^2)^{\frac{1}{2}}\right\}\right]^{\frac{1}{2}}$$

w = 2π.frequency

p_o = atmospheric pressure

h = porosity

$k = 1.4$

$$Y_i = \frac{w\rho_2(1-h)\left[R^2 + w^2\rho_1(h\rho_2 - h^2\rho_2 + \rho_1)\right]}{R^2 + w^2(1-h)^2(\rho_2 h + \rho_1)^2}$$

$$Y_r = \frac{w^2\rho_2^2\, R\, h(1-h)^2}{R^2 + w^2(1-h)^2(\rho_2 h + \rho_1)^2}$$

R = air resistance per unit length
= specific air resistance

ρ_1 = density of air

ρ_2 = density of fibre

Equipped with the data (transmission loss, weight per unit area, thickness, porosity and fibre density) of twenty randomly chosen fabrics a new value for air resistance namely the frequency dependent value (r_f), was computed from equation 6.1. The computed results show as indicated in figure 6.8 (for fabric A5) that r_f increases with frequency. This is in complete agreement with the previous discussion.

Using the above computed vaues of r_f an equation was fitted to the data, using stepwise linear regression analysis(107, 108) by computer. r_f was found to be equal to:

$$r_f = (A + Bf^{\frac{1}{2}}).C_h \qquad \text{.........(6.3)}$$

where:

f = frequency

C_h = (1 - porosity)

$$A = (9.39.10^{-4}R^2) - \frac{1.76.10^6}{R}$$

$$B = (0.33\,R) - \frac{2.62.10^6}{R}$$

$$R = \frac{\text{measured air resistance}}{\text{thickness of sample}}$$

= measured specific air resistance

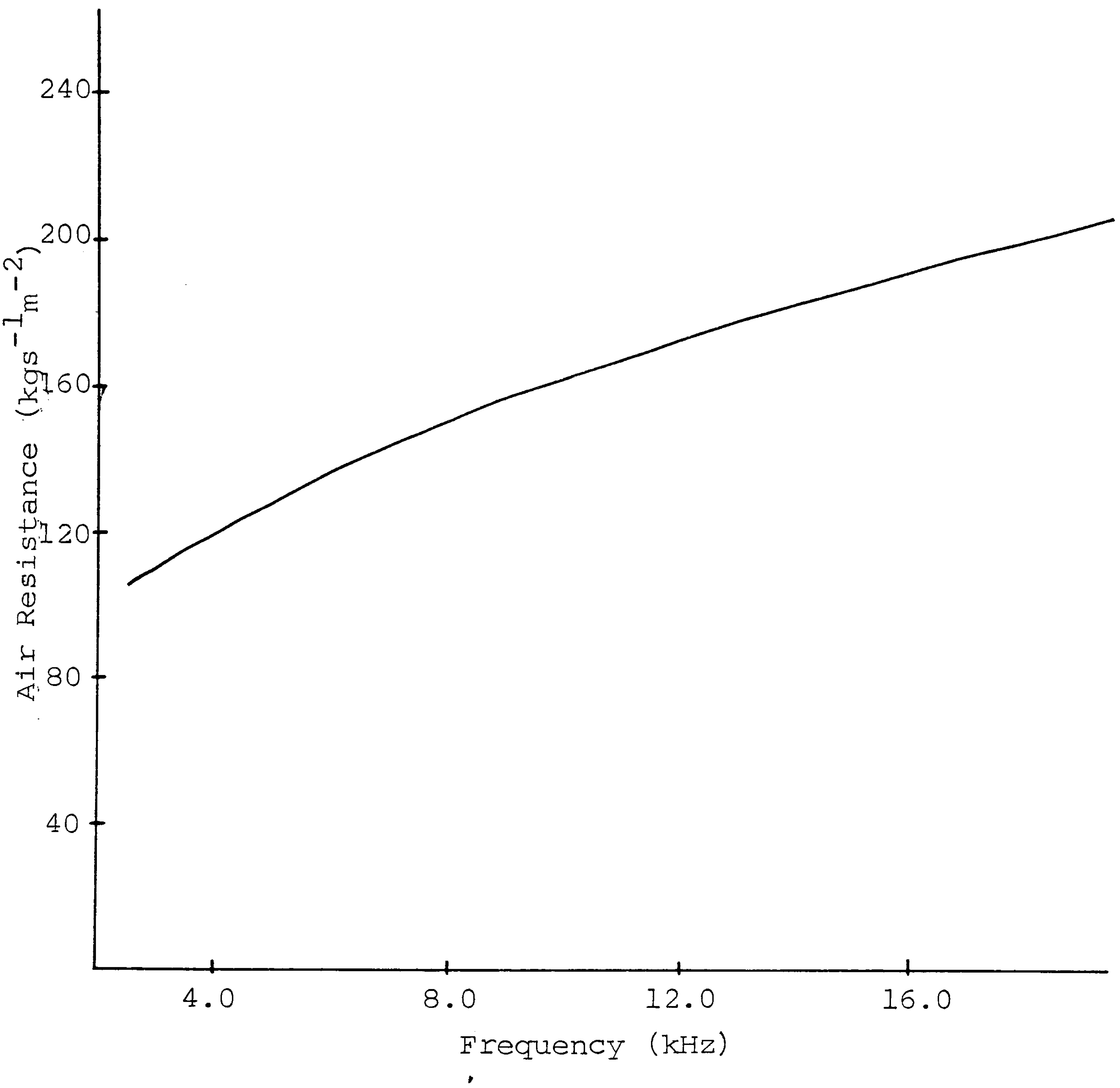


Figure 6.8 Calculated r_f (air resistance) versus frequency for fabric A5.

Equation 6.3 then was used to compute r_f at various frequencies for all fabrics. An attempt once more was made to compare the experimental transmission loss with the theoretically calculated transmission loss, taking into consideration the variation of air resistance with frequency. Since this time the theoretical transmission loss was calculated using the air resistance (r_f) computed from equation 6.3. Figures 6.9-6.12 show the results of this new approach for the fabrics plotted in figures 6.1-6.4.

In order not to break the continuity of this thesis, the comparison between the experimental and corrected theoretical (air resistance corrected for frequency) transmission loss for the rest of the fabrics is presented in appendix two, as figures A2.1-A2.141. Also in appendix three the correlation coefficient[116] between the experimentally measured and corrected theoretically calculated results for transmission loss is listed.

As can be seen from these figures and the correlation coefficients, for almost all of the fabrics, the correlation between the experimental and the corrected theoretically predicted transmission loss is very good. Hence it can be concluded that if the variation of air resistance with respect to frequency is taken into consideration, then the theory developed in chapter three predicts the transmission loss for all fabrics very well.

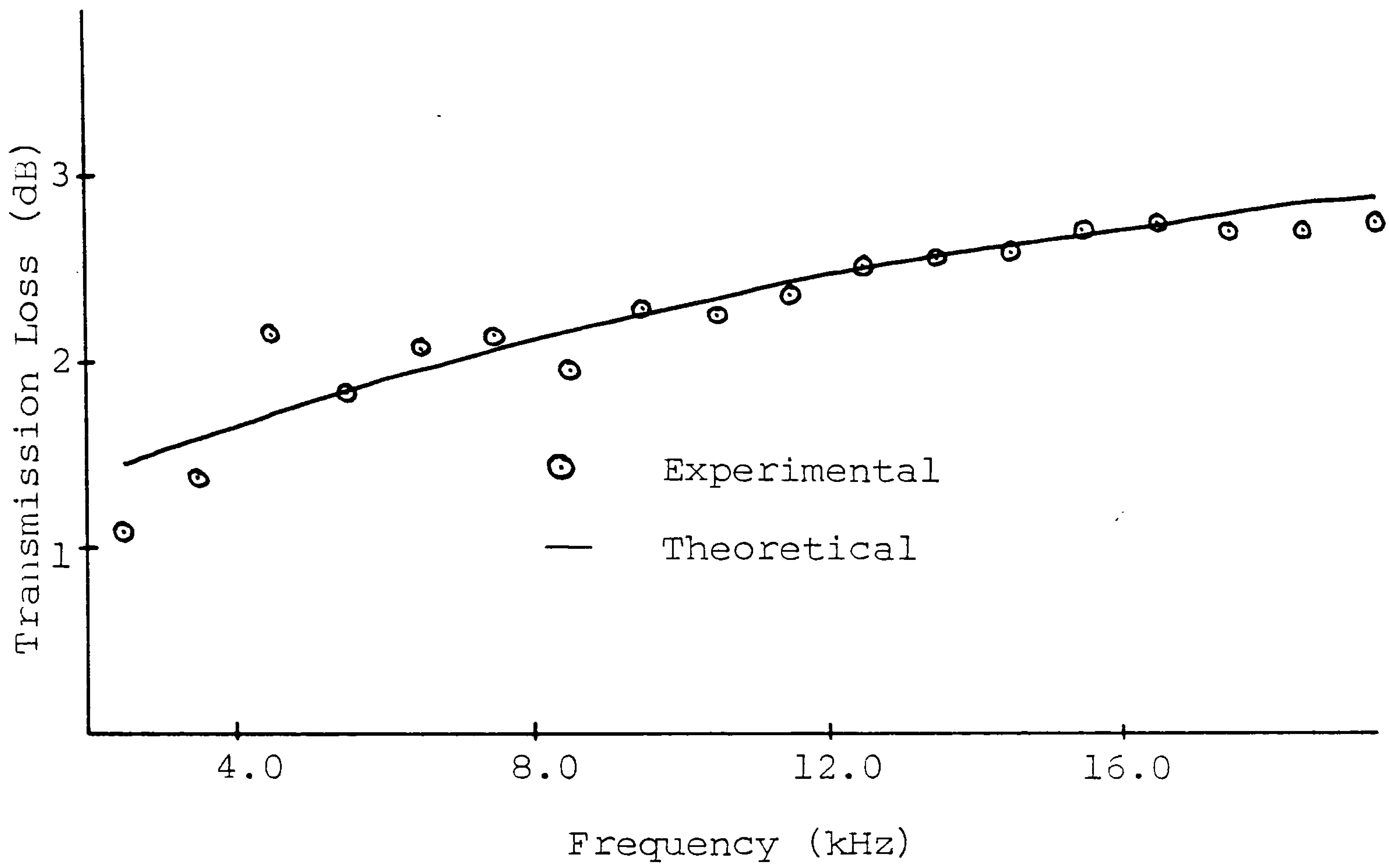


Figure 6.9 Experimental and theoretical transmission loss versus frequency for fabric A5.

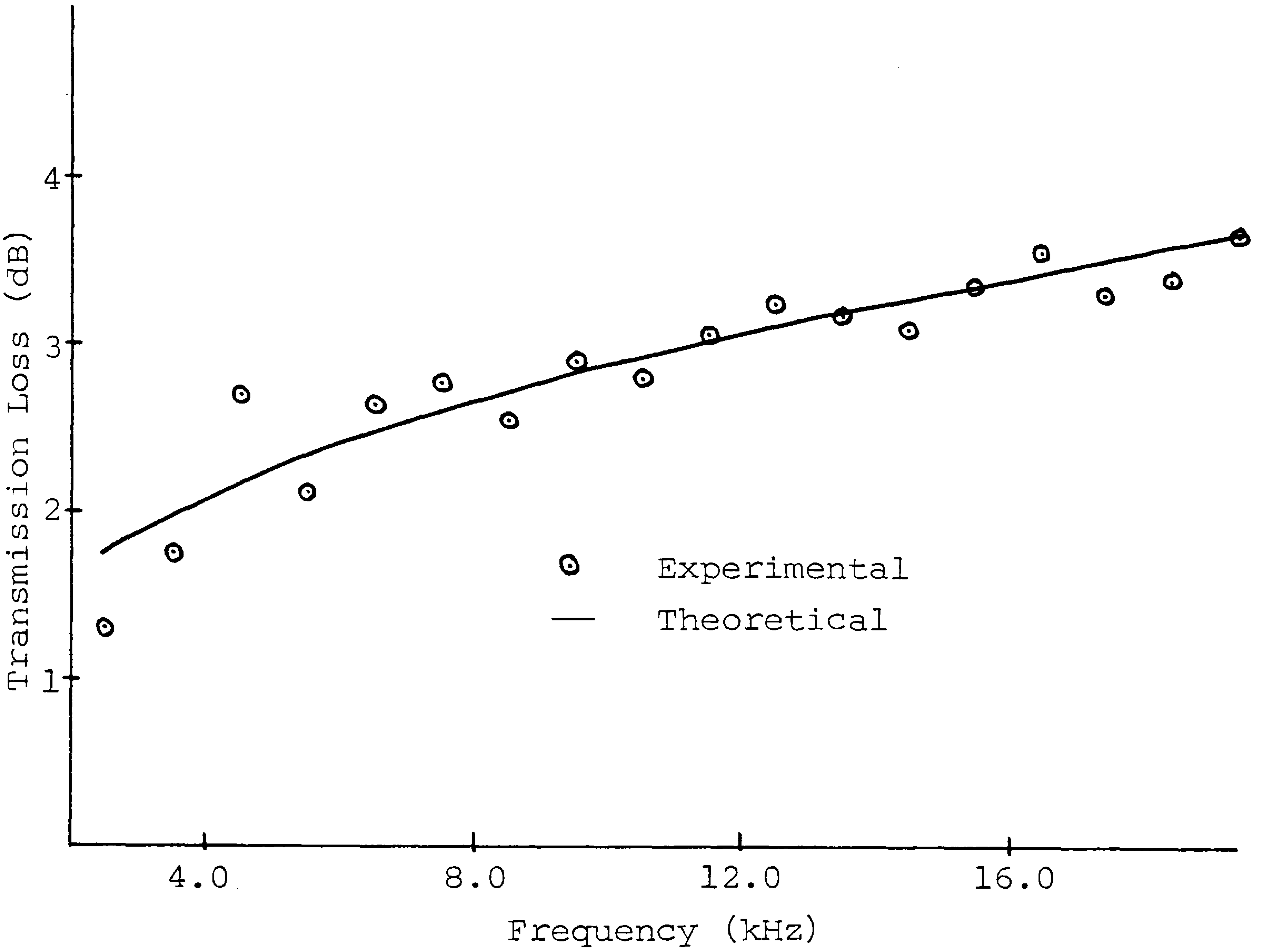


Figure 6.10 Experimental and theoretical transmission loss versus frequency for fabric G4.

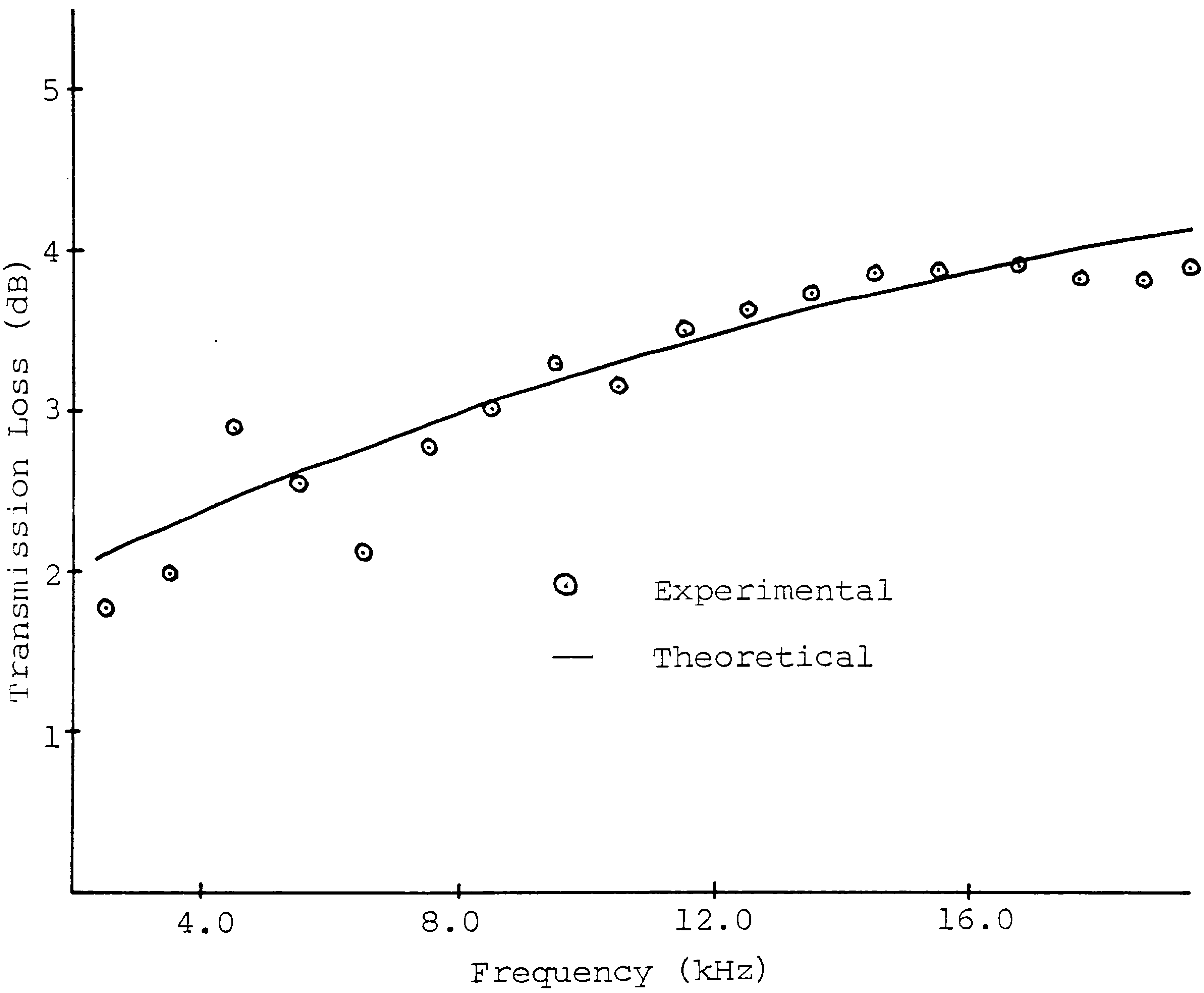


Figure 6.11 Experimental and theoretical transmission loss versus frequency for fabric B8.

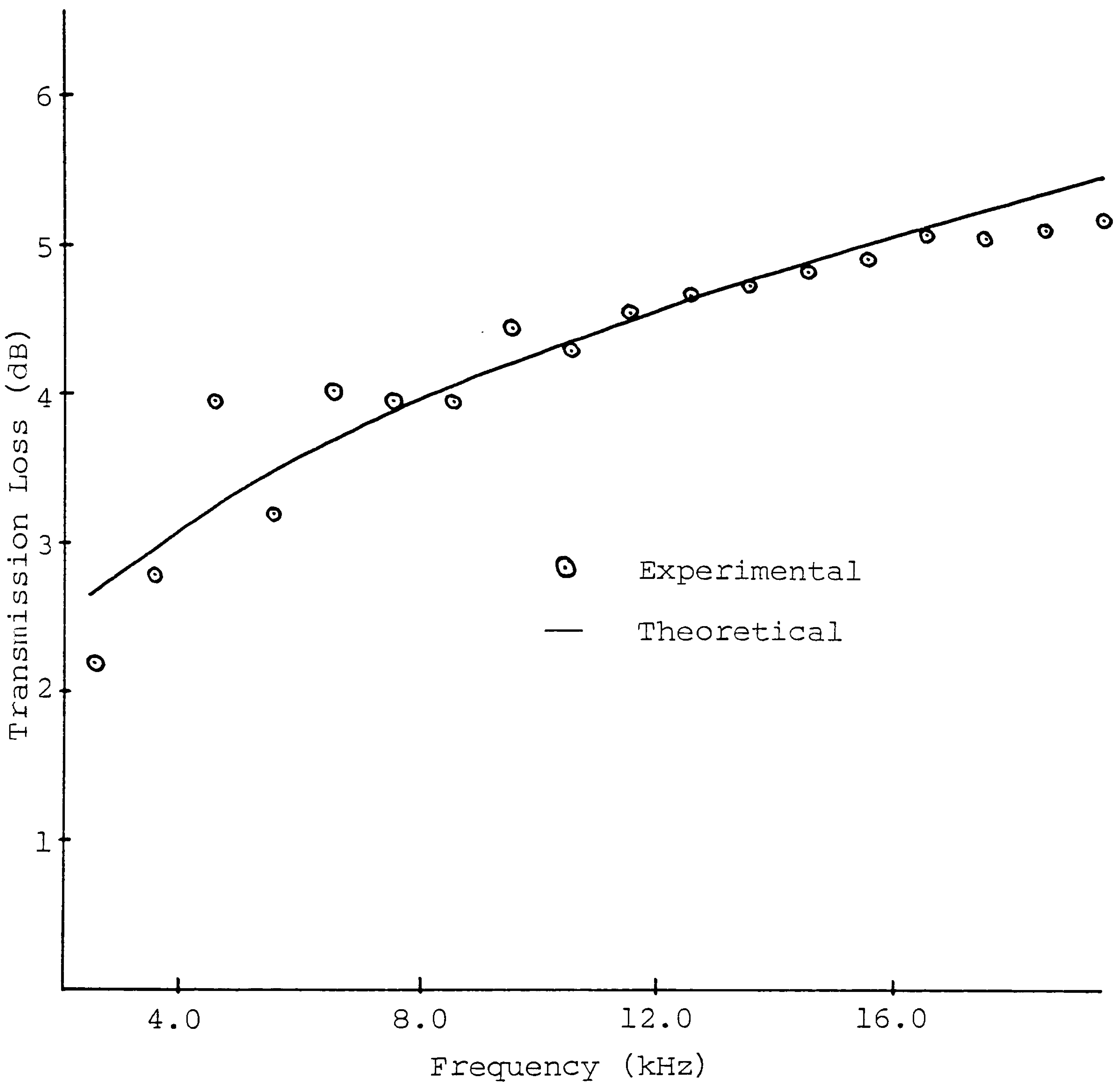


Figure 6.12 Experimental and theoretical transmission loss versus frequency for fabric G7.

CHAPTER SEVEN

EFFECT OF FABRIC PROPERTIES ON TRANSMISSION LOSS

7.1 Introduction

In the last chapter it was shown that the theory developed in chapter three after modification can be used to predict accurately the acoustic transmission loss as a function of frequency, for fabrics of different weight per unit area, thickness, air resistance, porosity and fibre density. In this chapter which is basically an extension of the same approach, with the help of theoretical equations (as discussed in the last chapter) and experimental results, an attempt will be made to investigate the dependence of transmission loss at a given frequency on each of the other fabric parameters. The ultimate aim of this chapter is to establish a basis for optimising and predicting the characteristics required for the least efficient (loudspeaker cover) and the most efficient (noise control partition) sound absorbing material as a realistic prerequiste for their manufacture.

7.2 Results and Discussion

7.2.1 Effect Of Fabric Weight Per Unit Area On Transmission Loss

The transmission loss was found to increase with the weight per unit area of the fabric as indicated in figure 7.1. It should be pointed out, however, that in plotting this graph, although only weight per unit area of the fabric was selected as the independent variable, no attempt was made to keep other fabric parameters (such as thickness and air resistance) constant. As can be seen from this figure, the overall trend is that the transmission loss increases with the weight per unit area of the fabric. However the experimental points seem to fall on different lines; for example the transmission loss due to fibres of 1.3dtex fibre fineness is always greater, indicating higher transmission loss with finer fibres. Clearly a given weight of fine fibres will exhibit a higher air resistance compared

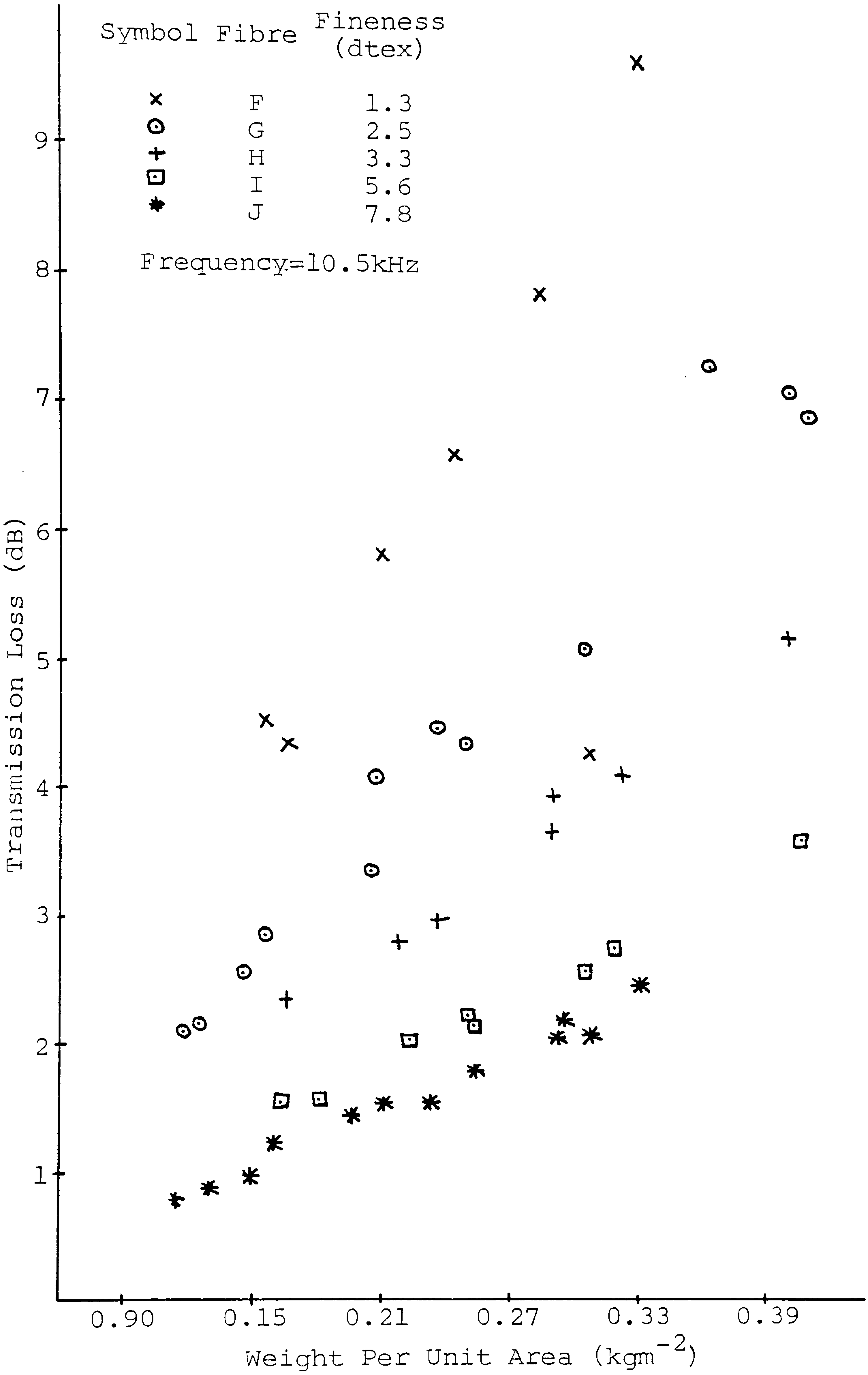


Figure 7.1 Influence of fabric weight per unit area on transmission loss

with coarser fibres and hence a higher transmission loss would be expected. Thus the scatter of the points in figure 7.1 can be attributed to the fact that other fabric parameters, which also will change the transmission loss are not constant

Figure 7.2 shows a plot of transmission loss versus frequency for two different fabrics, and within limits, the only difference between the two fabrics is their weight per unit area. This figure confirms the fact mentioned previously, that for a given material, the transmission loss increases with the weight per unit area of the fabric and also with frequency

In an attempt to investigate the dependence of transmission loss on fabric weight per unit area only, the theoretical equation for transmission loss, was applied to a model fabric in which the weight per unit area was arbitrarily varied whilst keeping fabric thickness, air resistance and fibre density constant. The results of this investigation are shown in figure 7.3-7.5. The results support the increase in transmission loss with fabric weight per unit area mentioned above.

At this stage it is interesting to consider the implications of this result. If the thickness of a fabric is kept constant then an increase in weight per unit area would of necessity increase the density of the fabric and thus decrease fabric porosity. In chapter five air resistance (r) was shown to be dependent upon the weight per unit area (m), thickness (t), porosity (h) of the fabric and fibre count (d), following an relationship of the form:

$$r = 15.73 + 141.1m - 0.012\frac{h^3}{(1-h)^2 d} + 29034\frac{t}{d} \qquad \ldots(7.1)$$

As can be seen from this equation, the situation being discussed in this section, (namely variation of weight per unit area whilst keeping thickness, air resistance and fibre density constant) in reality can be achieved by changing the fibre fineness. In other words, fabric weight per unit area can be increased, whilst keeping fabric thickness and air resistance constant, by packing an increased amount of

Curve	Thickness (mm)	Air Resistance ($kgs^{-1}m^{-2}$)	Weight Per Unit Area (kgm^{-2})
1	11.22	87	0.455
2	11.05	87	0.232

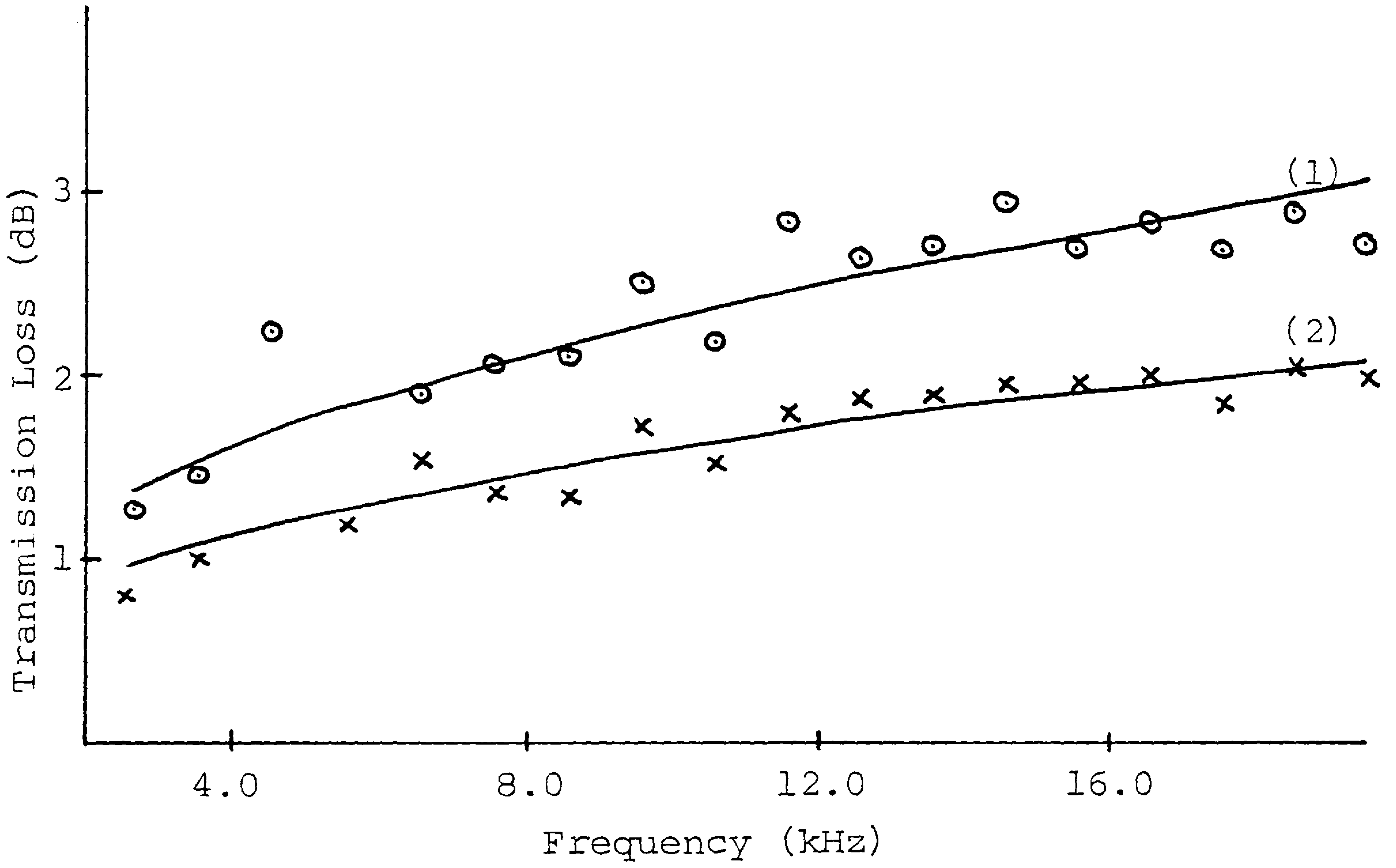


Figure 7.2 Transmission loss versus frequency for fabrics of different weight per unit area.

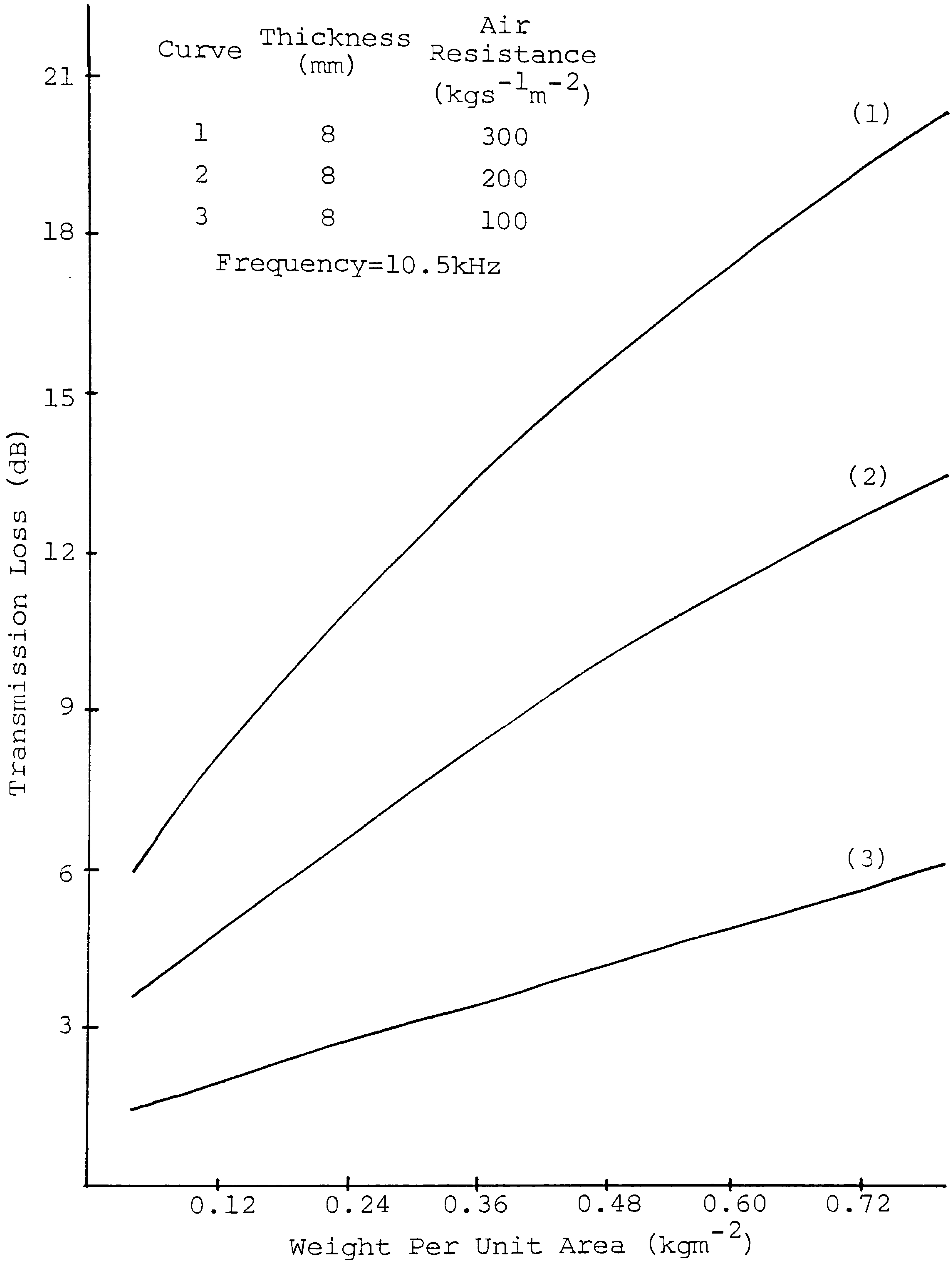


Figure 7.3 Transmission loss versus weight per unit area for fabrics of different air resistance

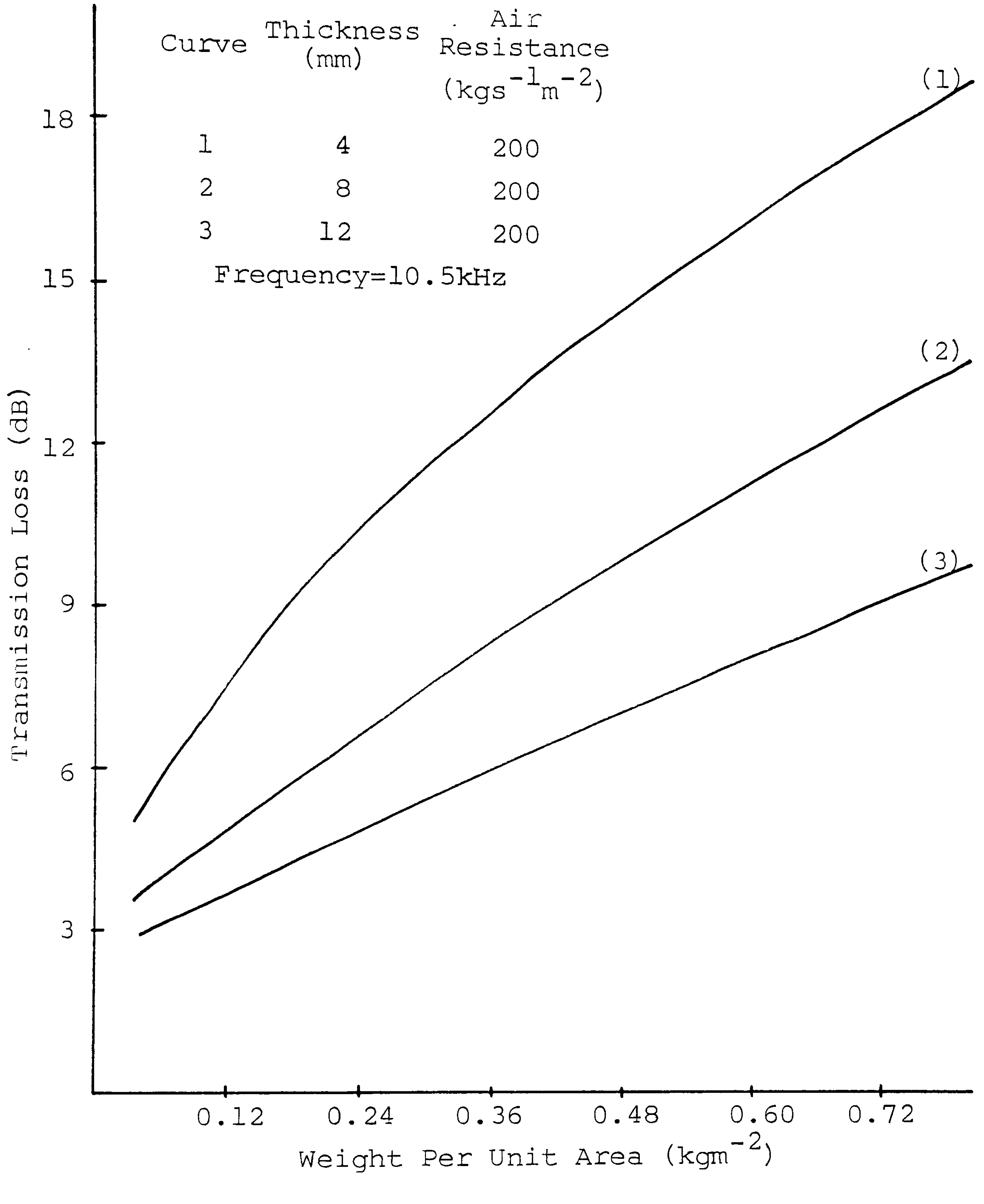


Figure 7.4 Transmission loss versus weight per unit area for fabrics of different thickness.

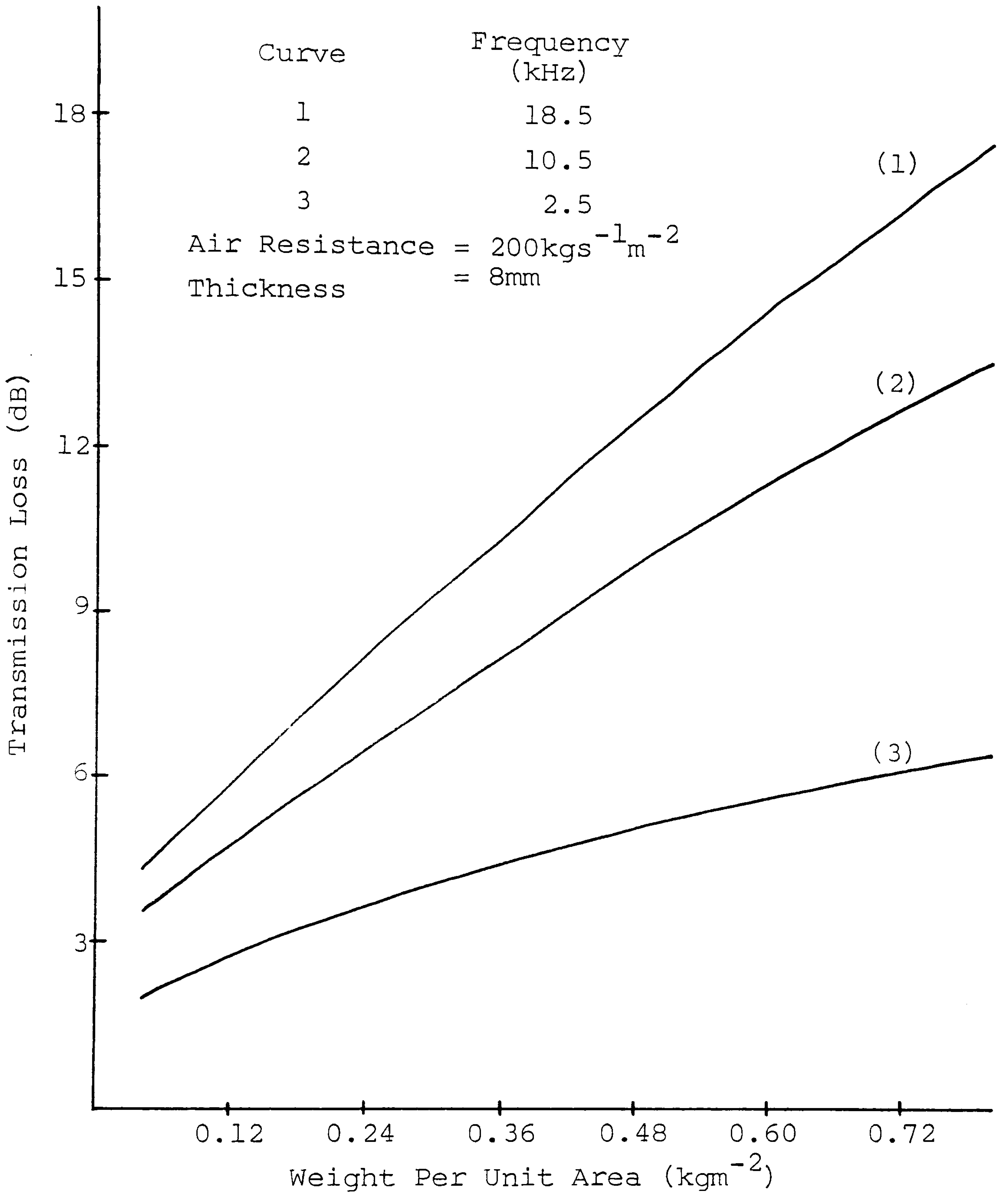
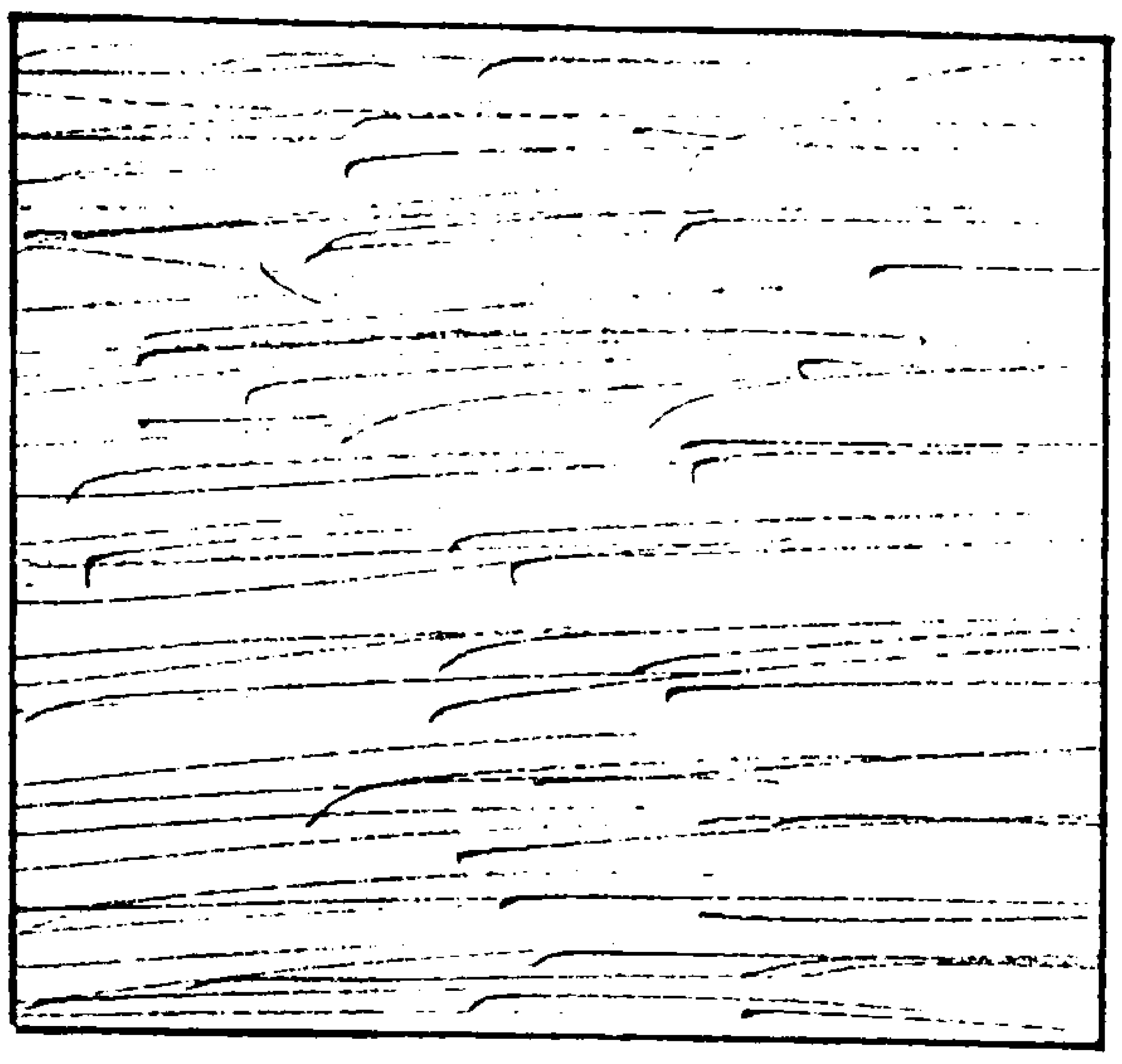


Figure 7.5 Transmission loss versus weight per unit area at different frequencies.

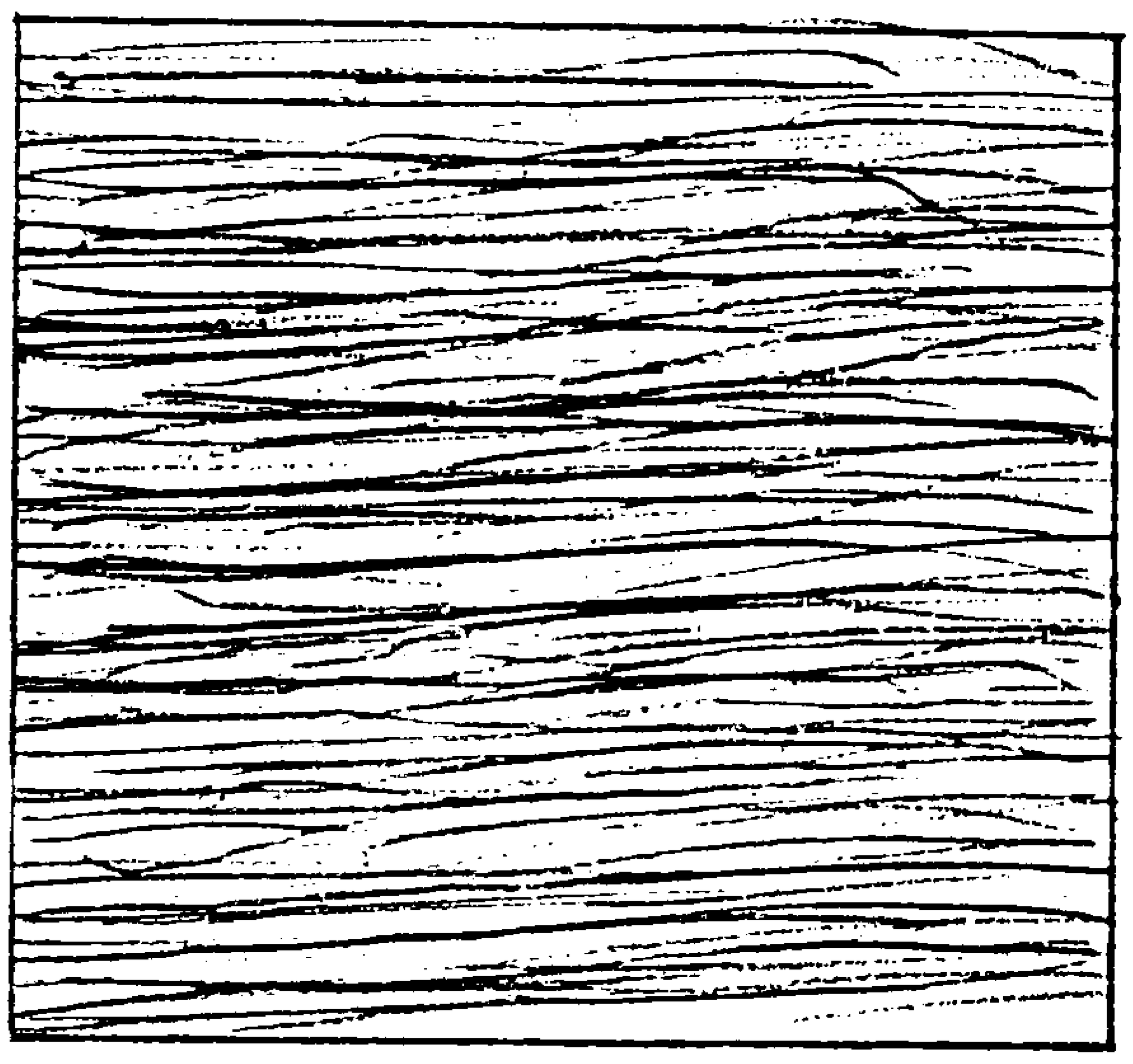
coarse fibres. As represented in figure 7.6, at low weight per unit area the fabric will be composed of very fine fibres and many air channels. However as the fabric increases in weight per unit area, the fine fibres (as indicated in figure 7.6) become replaced by coarse ones thus reducing the number of channels but increasing the dimensions of these channels. The decrease in the number of channels as far as air resistance is concerned will be compensated for by the increase in dimensions. In reality, the fabric will be quite complicated in structure in which the constituent fibres are mutually connected producing an integrated network.

Now consider the situation represented in figure 7.7, in which a fabric composed of very many fibres, which are packed together so as to leave between them interconnected channels (fabrics under consideration in this work are above 95% porous), is placed in the path of a sound wave. The pressure changes in the air due to the sound wave incident on the boundary surface of such a fabric must cause pressure changes within the fabric to occur. The initial incident sound wave thus would set up disturbances not only of the air in the channels of the fabric but also of the fibres themselves. Movement of the air in the pores of the fabric involves the expenditure of the initial sound wave energy against the forces required alternately to compress and rarefact the air and against viscous drag between the air particles and fibre surface. Energy also will be consumed by the motion of the fibres under the action of the force exerted upon them by the moving air. Energy consumed as a consequence of viscous drag is assumed constant in this section since air resistance remains constant, and as such the transmission loss as a result of viscous drag will remain constant as weight per unit area is increased. This can be represented by curve (a) in figure figure 7.8.

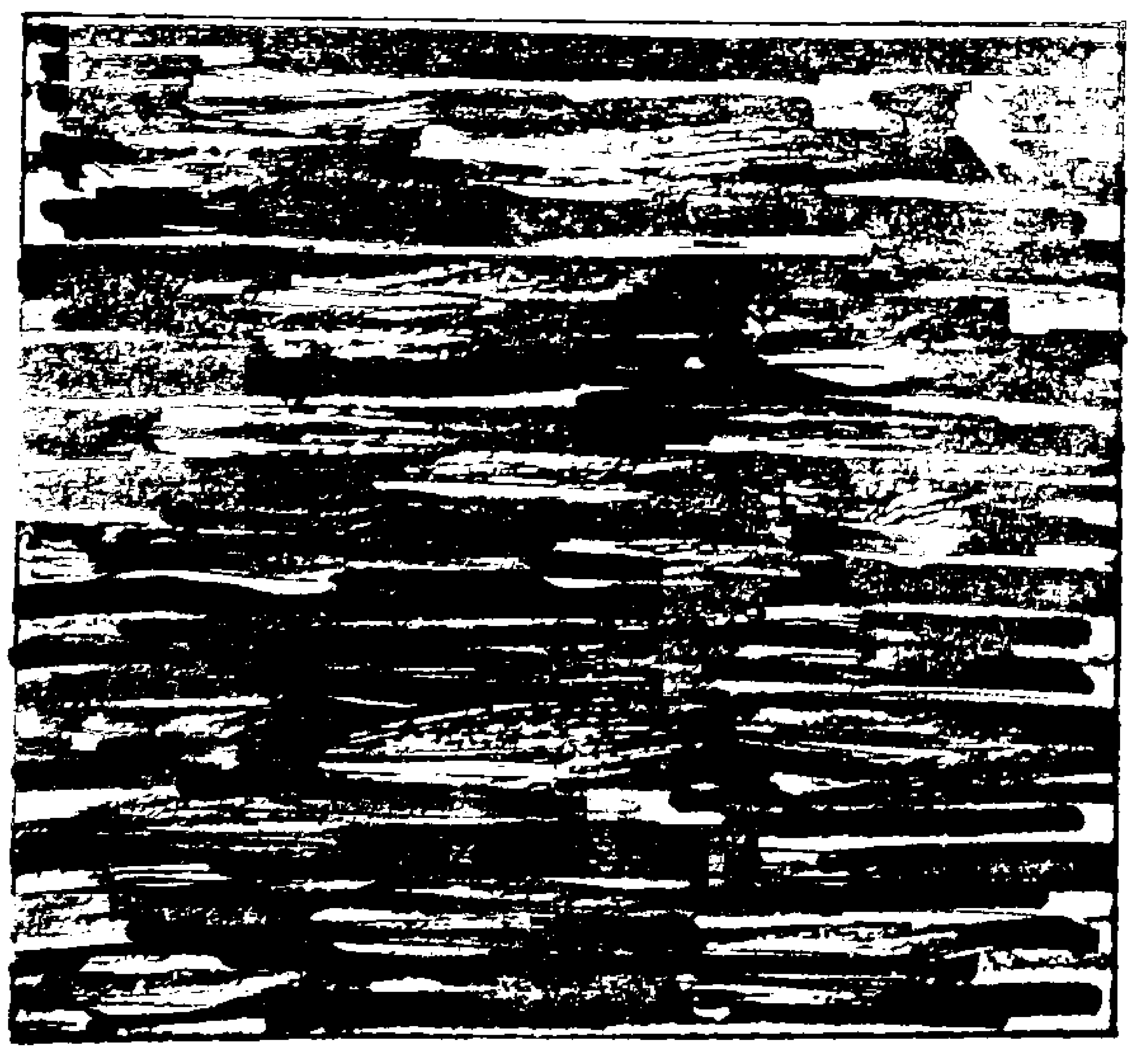
If the incident sound wave is of average variational pressure p, then every point in the fabric will experience a force proportional to the product of p and the area (A) of the fabric. This force (p A) will be opposed by



Low Weight Per
Unit Area



Intermediate Weight
Per unit Area



High Weight Per
Unit Area

Figure 7.6 Simplified representation of fabrics having same thickness and air resistance but different weight per unit area.

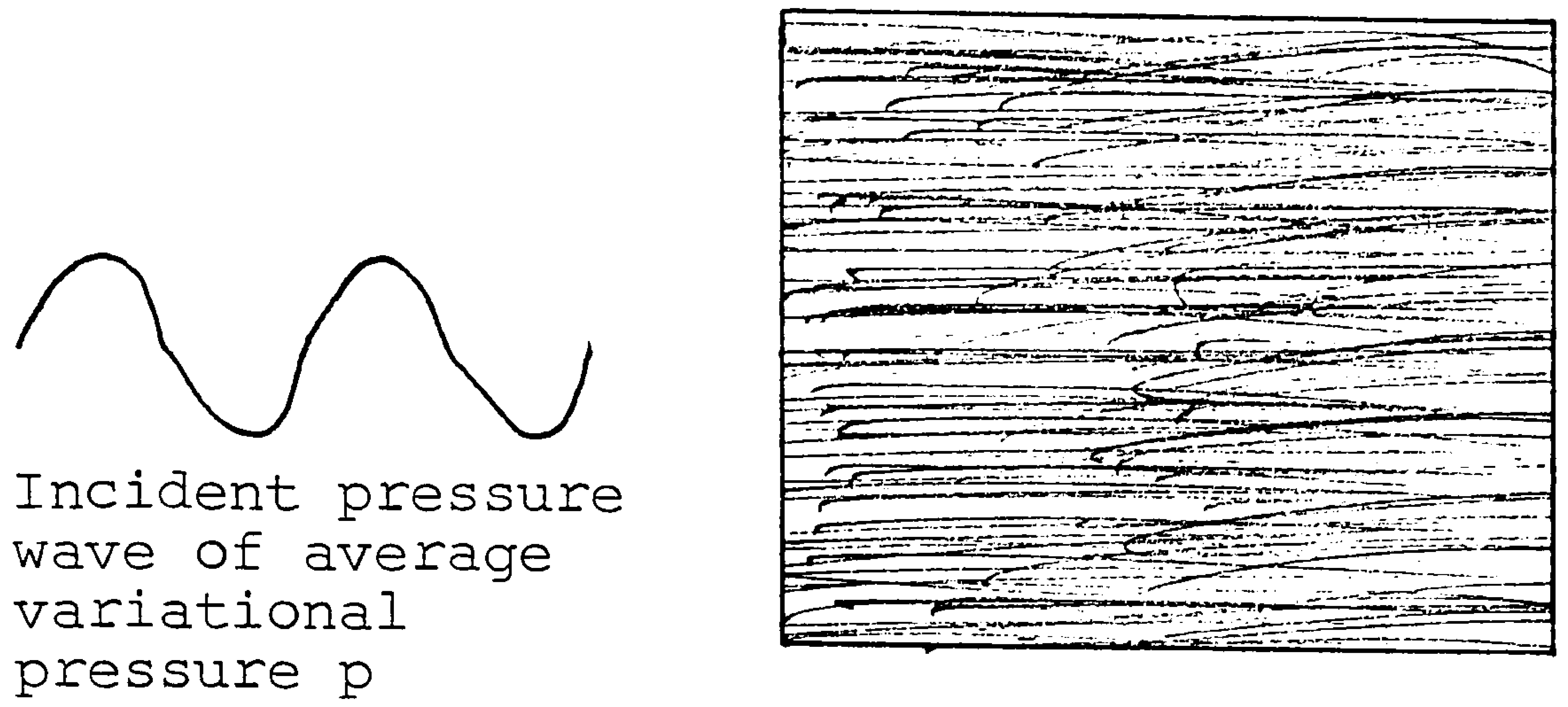


Figure 7.7 Simplified representation of a sound wave incident on a porous fabric.

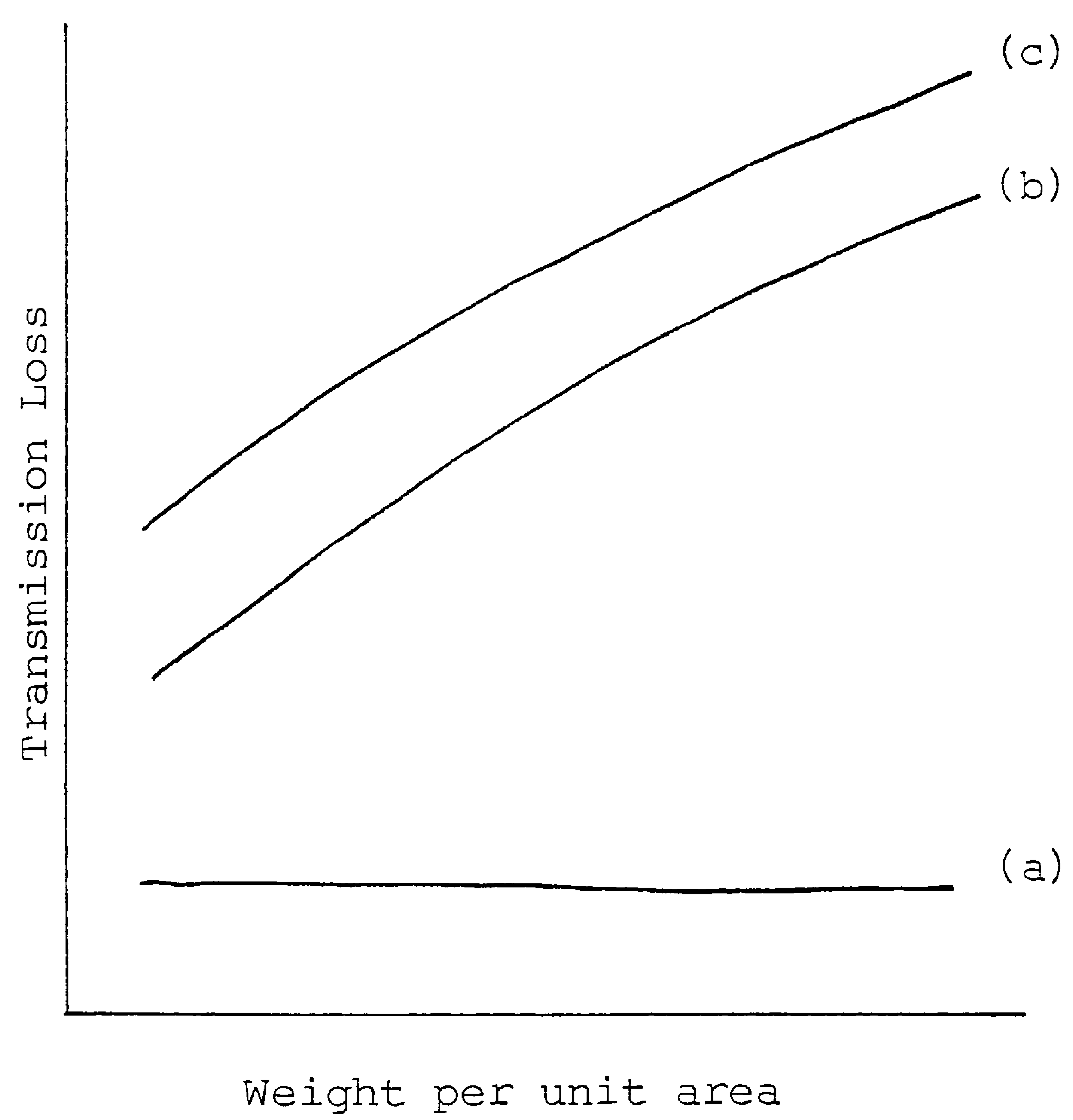


Figure 7.8 Schematic representation of processes responsible for transmission loss.

the sum of the products of respective mass multiplied by the respective acceleration namely that of the air and the fibres within the fabric; this can be expressed mathematically as:

$$pA = \sum_{i=0}^{n} m_i' a_i' + \sum_{i=0}^{m} m_i'' a_i''$$

where m' is the mass of fibre, a' is the acceleration of the fibre, m" is the mass of air contained in a channel, a" is the acceleration of the air in the channel, n is the total number of fibres in the fabric and m is the total number of air channels in the fabric, and by a force dependent on friction (constant). It is assumed that the vibrational displacement is proportional to the average variational pressure p in any portion of the fabric since the vibrations of the fabric will be very minute. Initially (for low weight per unit area) the mass reaction force of the fibres will be very small due to the fact that the total mass of the fibres in the fabric will be small and also the fibres will be very fine. As a consequence of the fabric being very porous, the air contained within the fabric will transmit the sound energy with the minimum loss. The mass reaction force of the air should decrease as the fabric increases in mass because of decreasing fabric porosity (or mass of air). The mass reaction force of the air will be very small compared with the mass reaction force of the fibres because of the low mass of air present in the fabric.

As the mass per unit area of the fabric increases (assuming that the degree of sound penetration remains the same) the additional fibre mass will provide further mass reaction force, as a consequence of the direct relationship between fibre mass and fabric weight per unit area. Hence transmission loss as a result of fibre mass reaction force will be directly proportional to fabric weight per unit area. However in reality as the fabric weight per unit area increases some of the interconnecting channels may become "displaced" or "sealed off" as represented in figure 7.9, as far as the incident sound wave is concerned. Consequently, if the incident pressure wave remains the same the air in these channels will vibrate at different amplitudes because

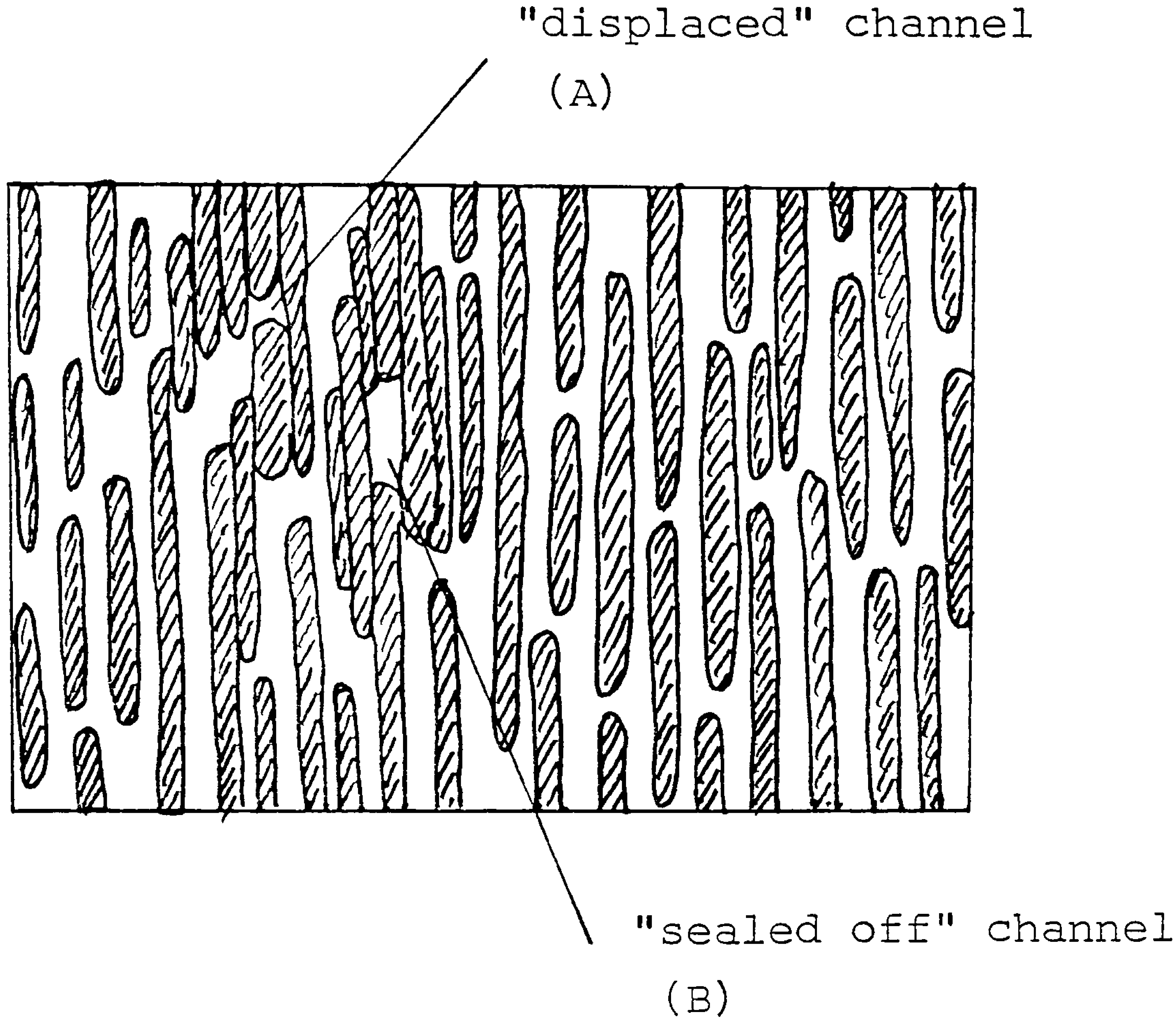


Figure 7.9 Schematic representation of the channels within the fabric, showing the "displaced" and the "sealed off" channels.

of their displaced position in relationship to the rest of the fabric as in figure 7.9. Hence the incident pressure wave will not suceed in vibrating the fibres which form the confining boundaries to these channels (channels A and B) to the same extent as "normal" channels. "Displaced" or "sealed off" channels will increase in number as the fabric decreases in porosity. The overall effect of such channels will be that they will reduce transmission loss as a result of fibre mass reaction force as the fabric decreases in porosity. Hence the increase in transmission loss (taking into consideration such channels) due to fibre mass reaction force should increase with fabric mass per unit area as represented by curve (b) in figure 7.8.

The combined effect of transmission loss as a result of fibre vibration and viscous resistance will result in the variation of transmission loss with fabric weight per unit area as indicated by curve (c) in figure 7.8 (curve (c) is the sum of curves (a) and (b)), and is in agreement with figures 7.3-7.5.

Before proceeding further it is interesting to consider the effects of reflection of the incident sound energy as it strikes the face of the fabric. The reflection effect will begin to occur significantly at fabric weights well above those under consideration, and as the fabric approaches zero porosity. The fabrics tested in the present work were above 95% porosity and as such the effects of reflection of sound were neglected. As the fabric porosity decreases and approaches zero (that is as the density of the fabric approaches the density of the fibres) the transmission loss as a result of reflection will begin to increase and as such the energy dissipated within the fabric will begin to decrease due to a reduction in the sound wave energy penetrating the fabric. However this situation should occur well above the range of the fabrics being discussed in this work.

Figure 7.3 indicates that for the complete range of fabric weights, a fabric of higher air resistance will have greater transmission loss. This may be attributed to the fact that transmission loss as a consequence of high viscous resistance will be greater in such fabrics.

Figure 7.4 indicates that for the range of fabric weights, a thinner fabric will have higher transmission loss. The reasons for this apparent anomaly will be discussed in the next section where the variation of transmission loss with thickness is considered.

In agreement with the discussion in the last chapter (namely that transmission loss increases with frequency) figure 7.5 indicates that for the range of fabric weights the transmission loss is greater at higher frequencies. This may be attributed to the fact that air resistance will increase with frequency and thus increase transmission loss as a result of viscous drag. As can be seen from this figure, for the range of weights, the increase in transmission loss is greater when going from 2.5kHz to 10.5kHz than when going from 10.5kHz to 19.5kHz. This is due to the fact that air resistance is not proportional to frequency but increases as $(\text{frequency})^{\frac{1}{2}}$.

7.2.2 Effect Of Fabric Thickness On Transmission Loss

Figure 7.10 shows a plot of transmission loss versus thickness. It should be pointed out, however that in plotting this graph, although only the thickness was selected as the independent variable, no attempt was made to keep other fabric parameters constant. As can be seen the overall trend is that transmission loss increases with thickness of the fabric but there is a high degree of scatter, which may be attributed to other fabric parameters.

Figure 7.11 shows a plot of transmission loss versus frequency for two different fabrics, the only apparent significant difference between the fabrics being their thickness. The results of this figure suggest an inverse relationship between fabric thickness and transmission loss, for fabrics of fixed weight per unit area and air resistance.

In an attempt to investigate the dependence of transmission loss on fabric thickness only, the theoretical equation for transmission loss discussed in the last chapter was applied to model fabrics in which the thickness arbitrarily was varied whilst keeping fabric weight per

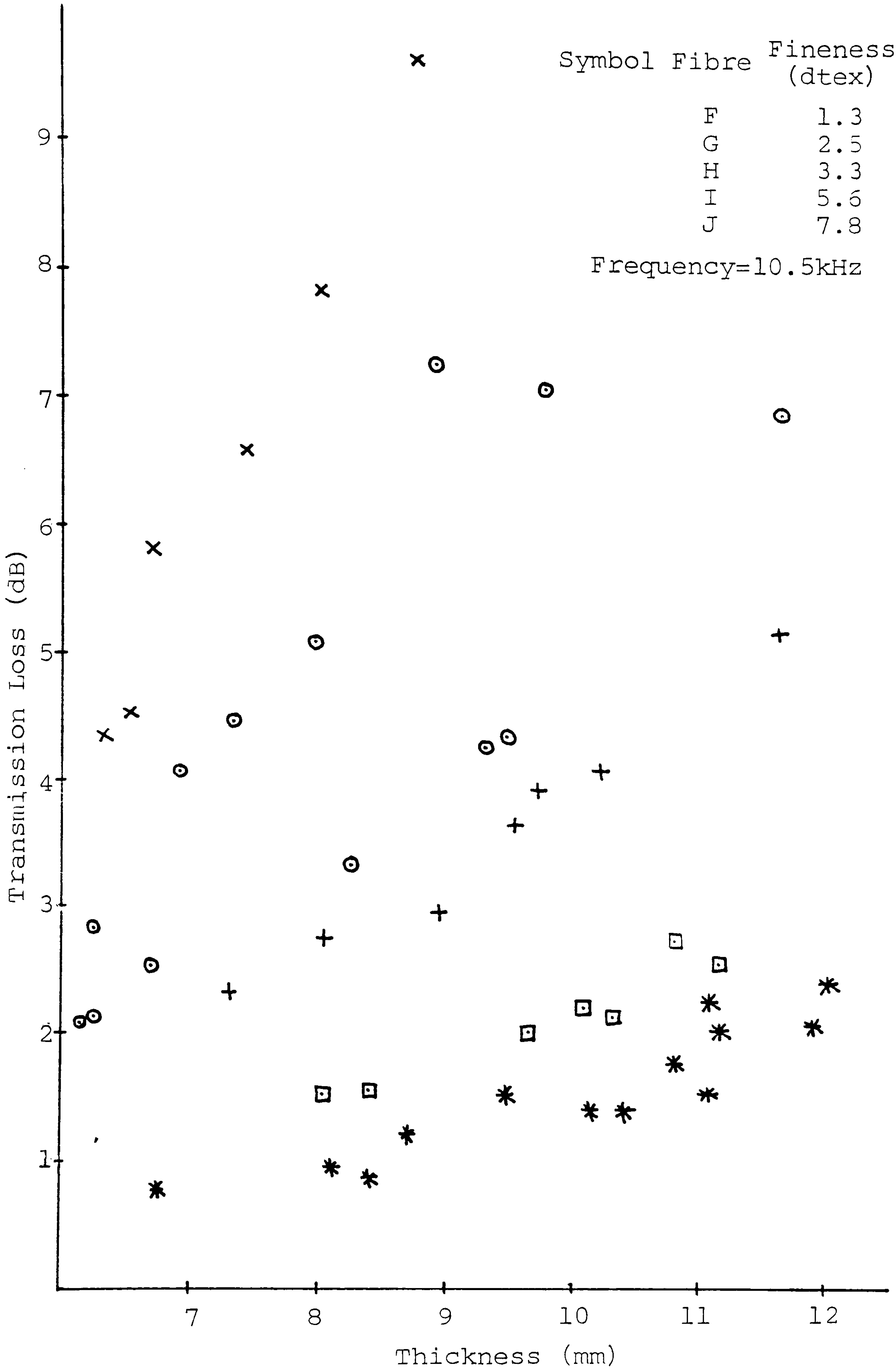


Figure 7.10 Influence of fabric thickness on transmission loss.

Curve	Thickness (mm)	Air Resistance ($kgs^{-1}m^{-2}$)	Weight Per Unit Area (kgm^{-2})
1	7.16	77	0.207
2	10.42	78	0.200

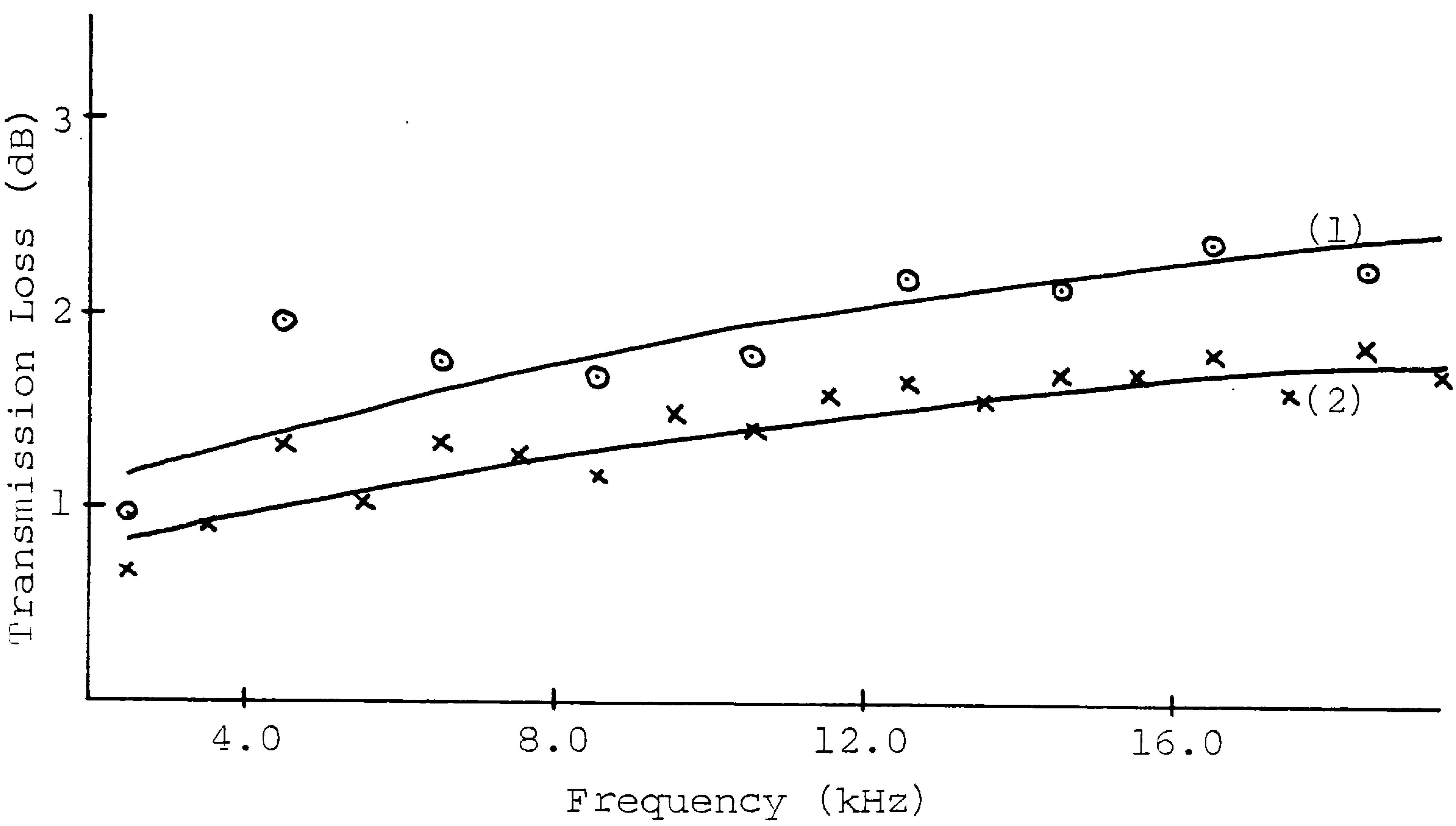


Figure 7.11 Transmission loss versus frequency for fabrics of different thickness.

unit area and air resistance constant. The results of this investigation are shown in figure 7.12-7.14. The results support the inverse relationship mentioned above.

Clearly if the weight per unit area of the fabric is kept constant then an increase in thickness would of necessity decrease the density of the fabric and thus increase the porosity of the fabric. Consequently as represented in figure 7.15, very thin fabrics will have the fibres very closely packed with few channels, and the number of channels present will increase as the fabric increases in thickness.

Once again consider the energy consumption of a sound wave by a fabric placed in its path. As in the last section, the incident sound wave energy will be consumed as a consequence of the viscous drag resistance between the surface of the fibres and air as the sound wave passes through the fabric, and as a consequence of vibrations (mass reaction force) of the fibres. However transmission loss due to the mass reaction force should remain basically constant, as the mass of the fibres present will be constant. In reality as discussed in the last section energy consumption as a result of the mass reaction force will change slightly as the fabric thickness increases because the so called "displaced" and "sealed off" channels will begin to disappear as the fabric increases in porosity. Transmission loss as consequence of this effect can be represented by means of curve (A) in figure 7.16.

The air resistance of a fabric which was defined earlier as the reciprocal of air permeability (or the ratio of applied pressure differential measured between the two sides of the fabric to the air velocity through and perpendicular to the two sides of the fabric), also can be defined as the time in seconds for unit volume of air to pass through unit area of the fabric under an applied pressure differential measured between the two sides of the fabric. It is this quantity that is being kept constant along with the fabric weight per unit area, as the fabric thickness is varied. The specific air resistance defined as the air resistance per unit length is a measure of the

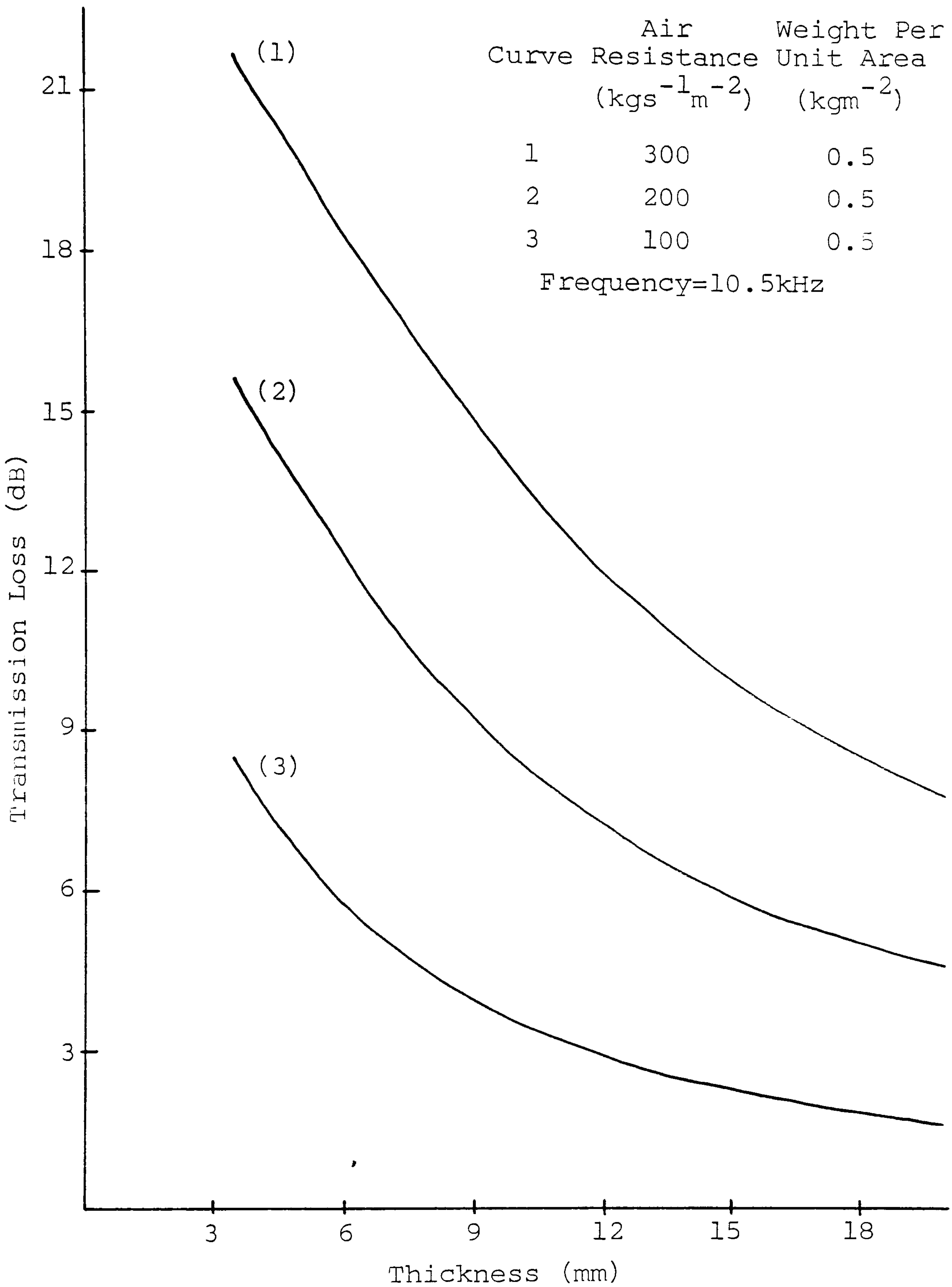
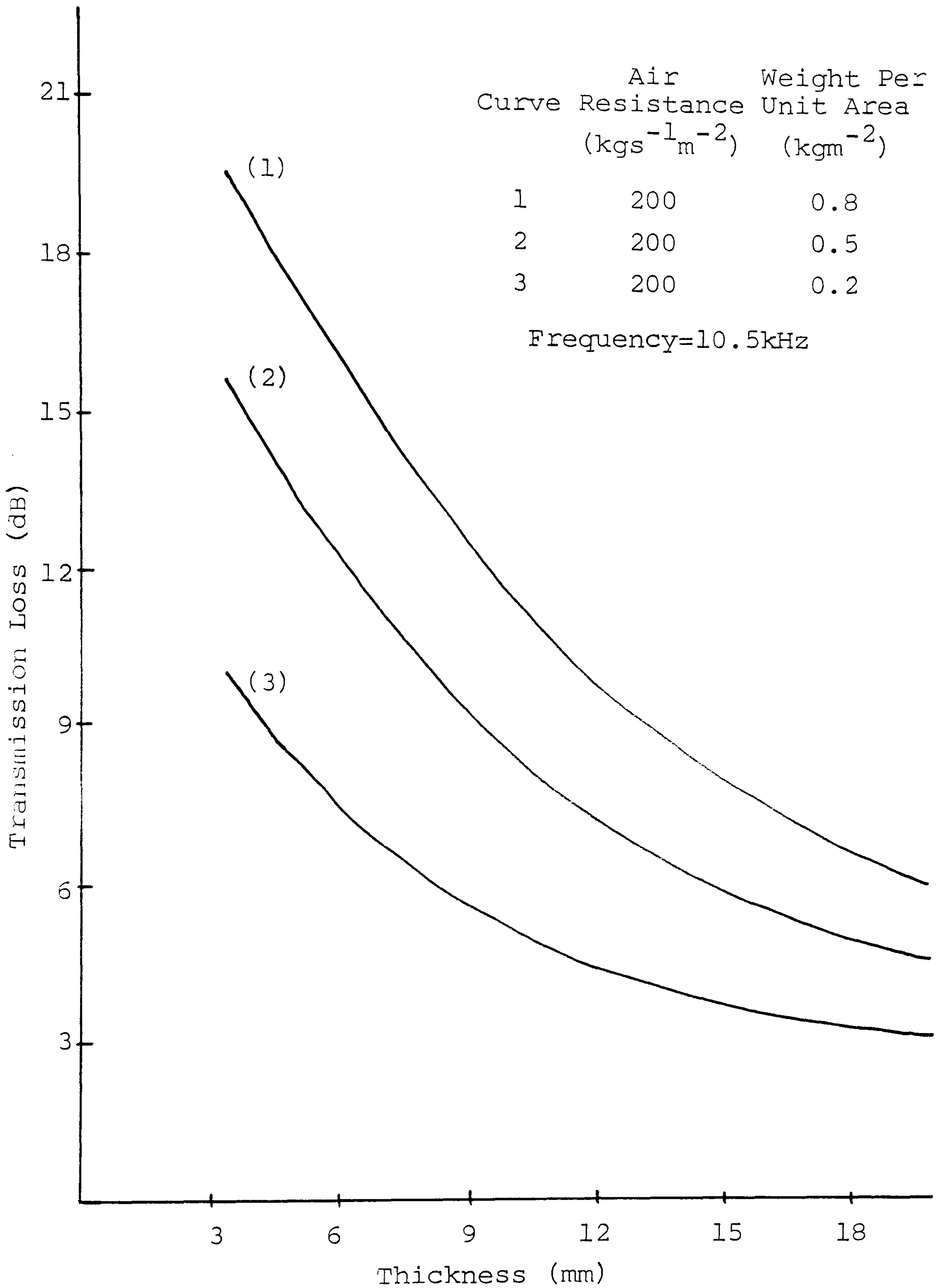


Figure 7.12 Transmission loss versus thickness for fabrics of different air resistance.



<u>Figure 7.13</u> Transmission loss versus thickness for fabrics of different weight per unit area.

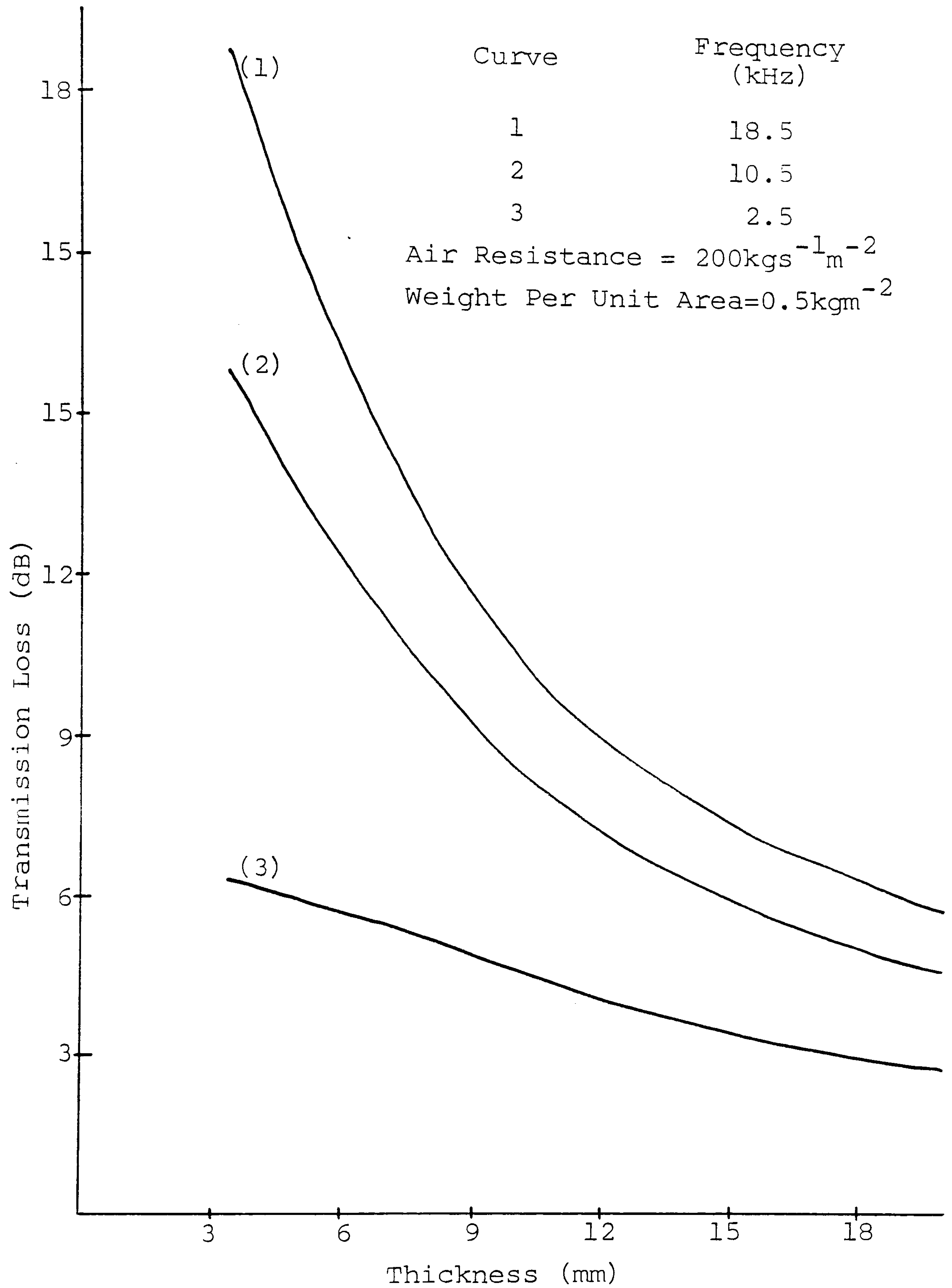


Figure 7.14 Transmission loss versus thickness at different frequencies.

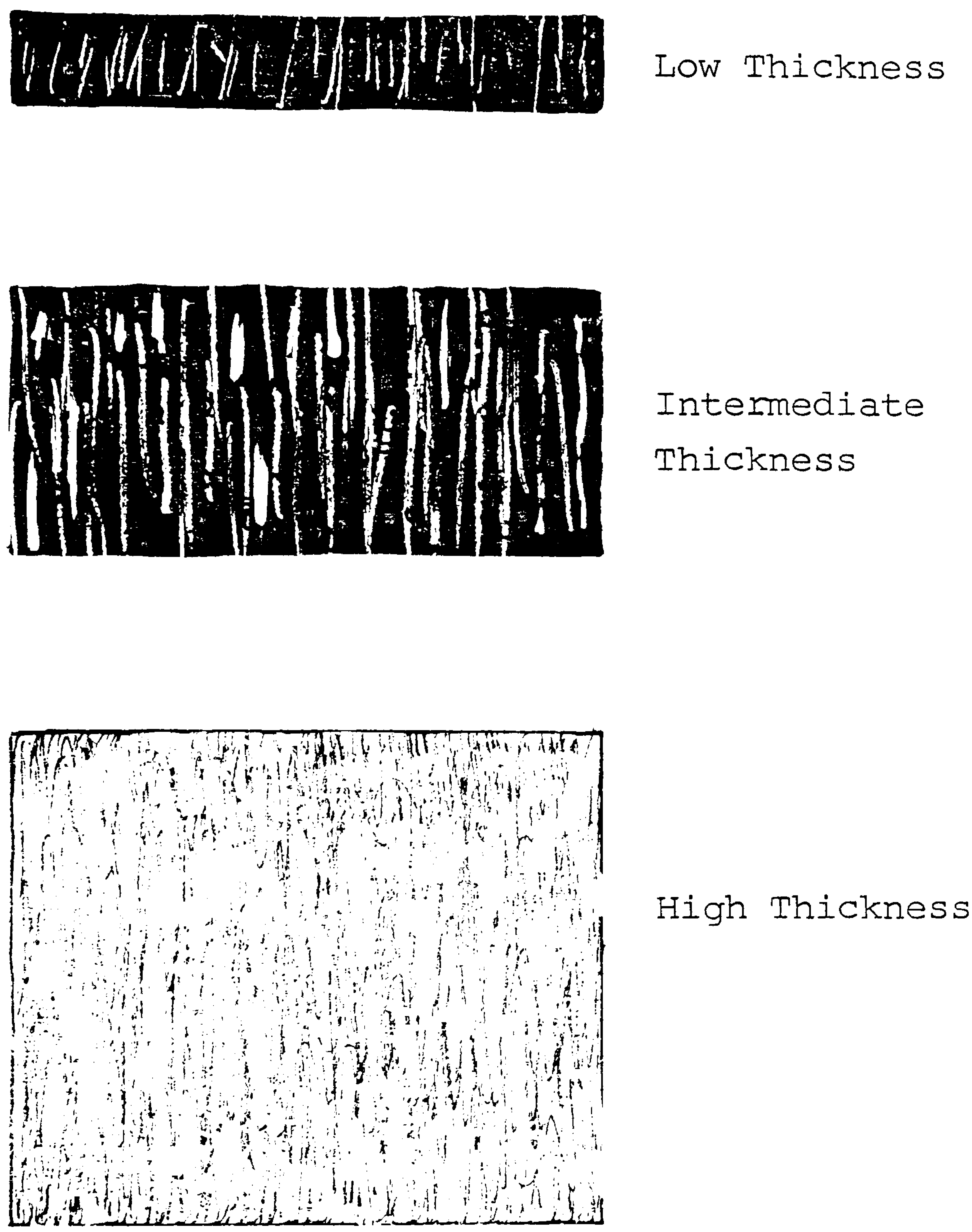


Figure 7.15 Simplified representation of fabrics having same weight per unit area and air resistance but different thickness.

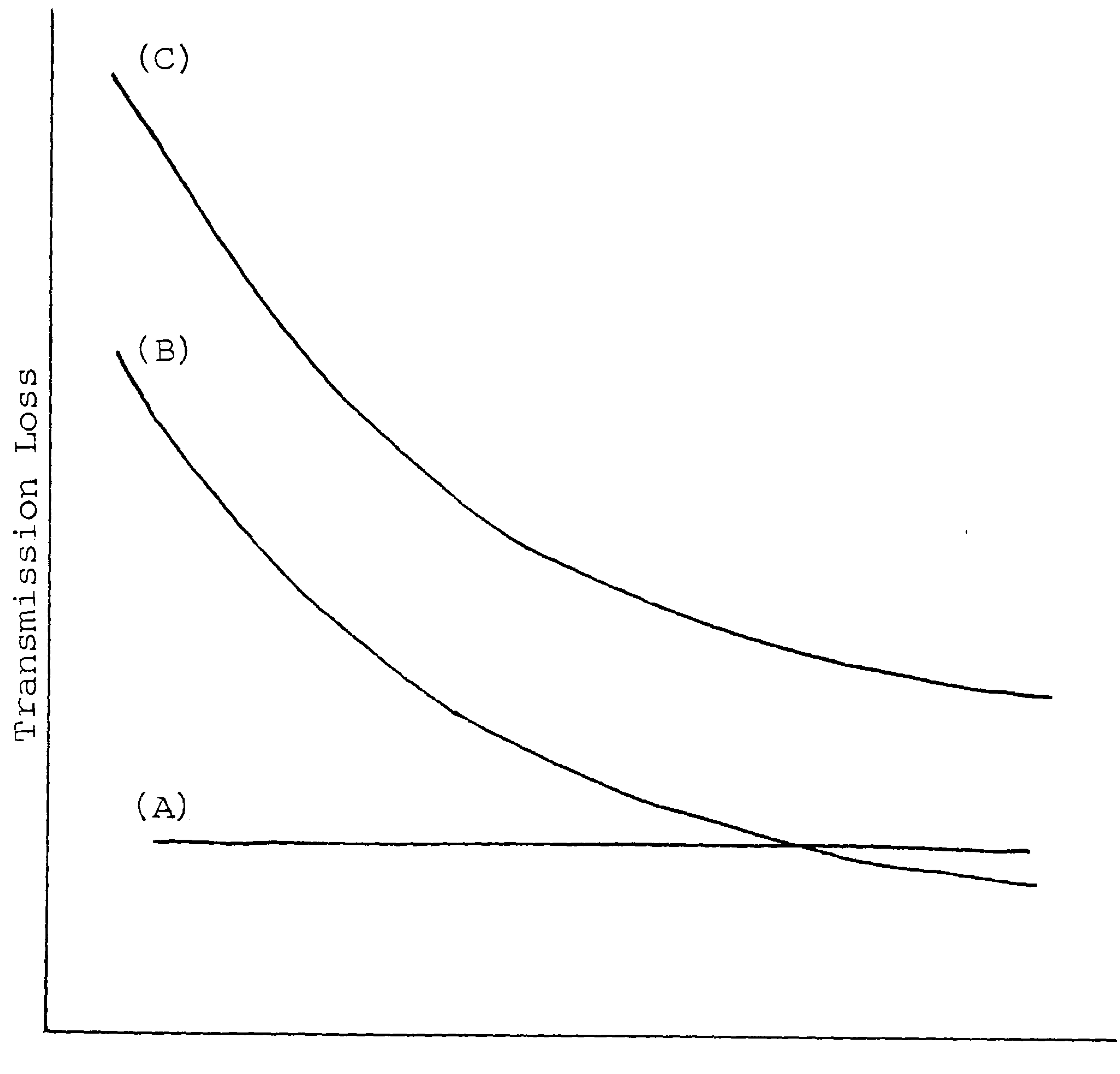


Figure 7.16 Schematic representation of processes responsible for transmission loss.

difficulty with which air can be blown through unit thickness of the sample, and is the all important factor which will govern transmission loss as a result of viscous resistance.

It is fairly easy to see that as the fabric increases in thickness (resulting in a decrease in density and increase in porosity) the difficulty with which unit volume of air can be blown through unit area of the fabric per second will decrease, and hence the energy consumed in blowing the air will decrease. (An analogy to this is squeezing a liquid through tubes of different diameter. If unit volume of the liquid is to be squeezed per unit area per second, then more energy will be required to squeeze unit volume through the lower diameter tube, and the energy required will decrease as the tube diameter increase). Hence the viscous resistance offered to the flow of air will be directly proportional to the porosity of the fabric. As porosity, which was calculated using the relationship:

$$\text{Porosity} = 1 - \frac{\text{density of fabric}}{\text{density of fibre}}$$

is inversely proportional to the fabric thickness, the transmission loss as a consequence of viscous resistance also will be inversely proportional to the thickness of the fabric. Hence transmission loss as a result of viscous resistance will decrease with the thickness of the fabric as indicated by curve (B) in figure 7.16.

The combined effect of transmission loss as a result of fibre vibration (curve (A)) and viscous resistance (curve (B)) will result in transmission loss as indicated by curve (C) in figure 7.16 and is in agreement with figures 7.11-7.14.

Figure 7.12 indicates that for all thicknesses, a fabric of higher air resistance will have higher transmission loss. The reason for this is obvious since in the case of high resistance fabrics more energy will be expended in overcomming viscous resistance at any given thickness.

Figure 7.13 indicates that for all thicknesses, a heavier fabric will absorb more sound. This is in agreement with the discussion in the last section and is a consequence of more fibres being present in the fabric such that more energy will be expended as a result of their mass reaction force.

As in the last section and in agreement with the discussions of the last chapter, figure 7.14 indicates that for all thicknesses the transmission loss is greater at high frequencies. This may be attributed to the fact that the specific air resistance increases with frequency as $(\text{frequency})^{\frac{1}{2}}$. As can be seen from this figure, for all thicknesses the increase in transmission loss is greater in going from 2.5kHz to 10.5kHz than in going from 10.5khz to 19.5kHz, this may be attributed to the fact that specific air resistance is not proportional to the frequency but to $(\text{frequency})^{\frac{1}{2}}$.

7.2.3 Effect Of Fabric Air Resistance On Transmission Loss

Transmission loss was found to increase with the air resistance of the fabric as indicated in figure 7.17. It should be pointed out, however, that in plotting this graph, although only air resistance of the fabric was selected as the independent variable, no attempt was made to keep other fabric parameters constant. As can be seen from this figure, the correlation between air resistance and transmission loss is very good irrespective of other fabric parameters. The slight scatter that does exist can be attributed to the fact that other parameters are not constant. For example at a given air resistance the heavier fabrics will have higher transmission loss for reasons discussed in the last section.

Figure 7.18 shows a plot of transmission loss versus frequency for three different fabrics of very nearly constant weight per unit area and thickness but different air resistance. This figure confirms the fact mentioned previously that for a given material, the transmission loss increases with the air resistance of the fabric and also that transmission loss increases with frequency.

Once again in an attempt to substantiate the dependence of transmission loss on fabric air resistance

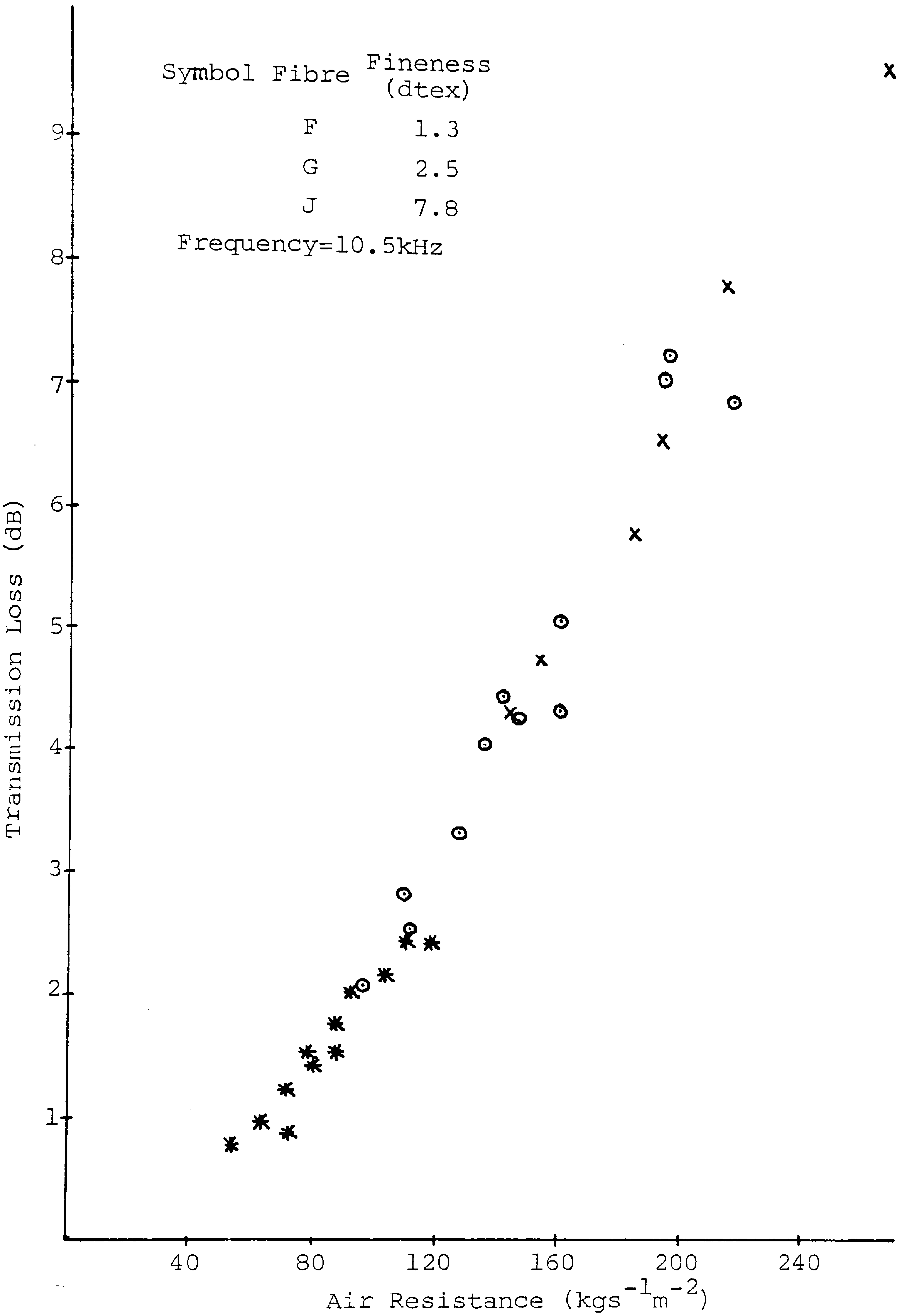


Figure 7.17 Influence of fabric air resistance on transmission loss.

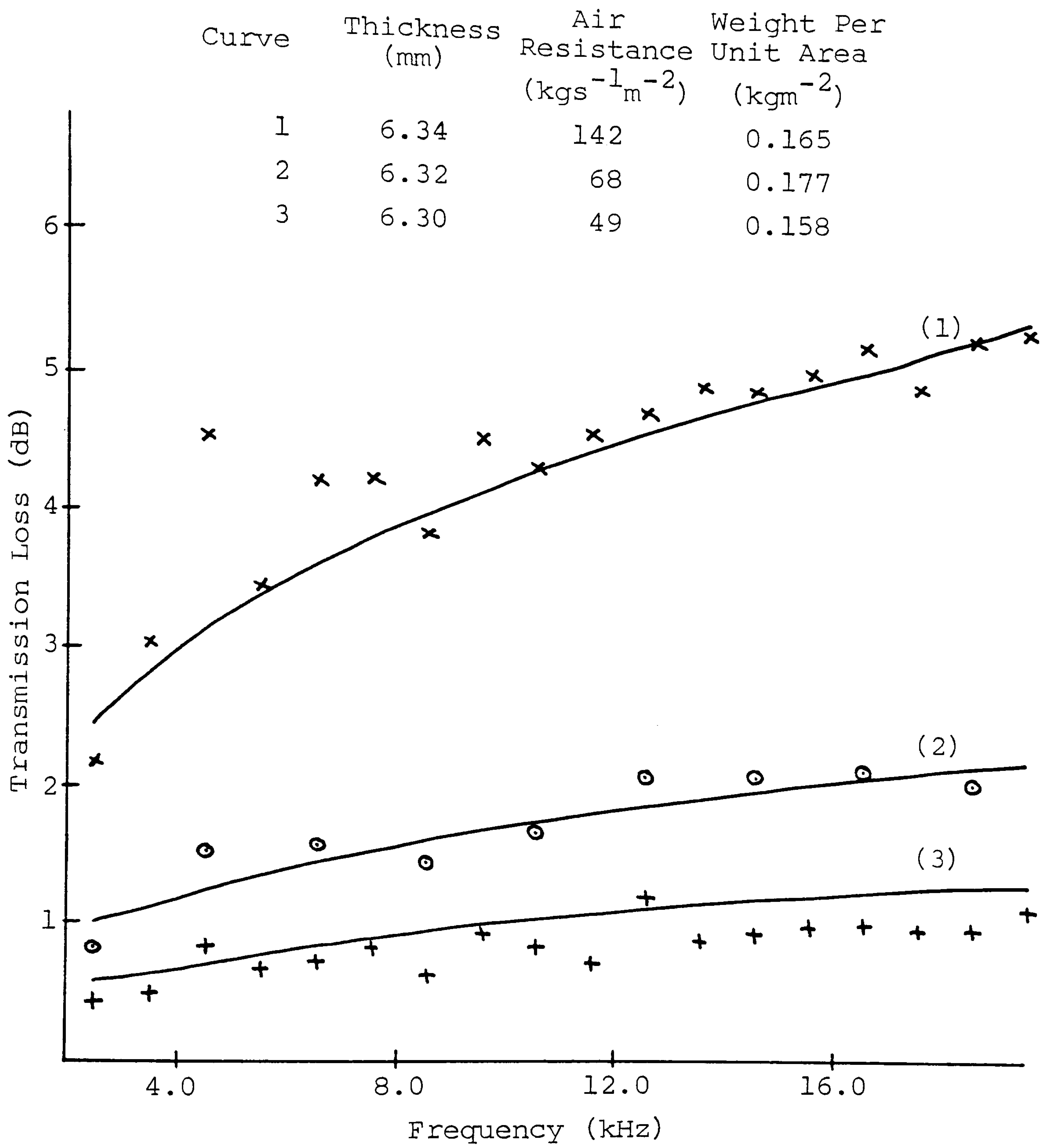


Figure 7.18 Transmission loss versus frequency for fabrics of different air resistance.

only, the discussed theoretical equation was applied to a model fabric in which the fabric air resistance was arbitrarily varied whilst keeping the fabric thickness and weight per unit area constant. The results of this investigation are shown in figures 7.19-7.21 and indicate a fairly linear relationship between transmission loss and air resistance for fabrics of constant weight per unit area and thickness.

If the fabric weight per unit area and thickness are kept constant then the fabric porosity also will remain constant. As mentioned earlier air resistance (r) was shown to be dependent upon the weight per unit area, thickness and porosity of the fabric and fibre fineness, following a relationship represented by equation 7.1. As can be seen from this equation, the situation being discussed in this section (namely variation of air resistance whilst keeping fabric thickness and weight per unit area constant) in reality can be achieved by changing the fibre fineness. If all other factors in the equation are kept constant, then air resistance will be inversely proportional to the fibre count. In other words, fabric air resistance can be increased whilst keeping fabric weight per unit area and thickness constant by packing the same mass of finer fibres. Thus the same mass of finer fibres packed in the same volume will provide higher resistance, since the total fibre surface area exposed to the flowing air will be greater. Figure 7.22 shows three simplified fabrics all of constant weight per unit area, thickness and porosity. At low air resistance, the fabric will be composed of channels of large dimensions and the fibres present will be very coarse. As the fabric increases in air resistance, the fibres will become finer and the channels will increase in number but decrease in diameter (since porosity is constant).

Once again consider the energy consumption of a sound wave incident on fabrics shown in figure 7.22. As before the incident sound wave energy will be consumed as a consequence of the viscous resistance between the surface of the fibres and air and also as a consequence of the mass reaction forces. The resistance of a fabric of given

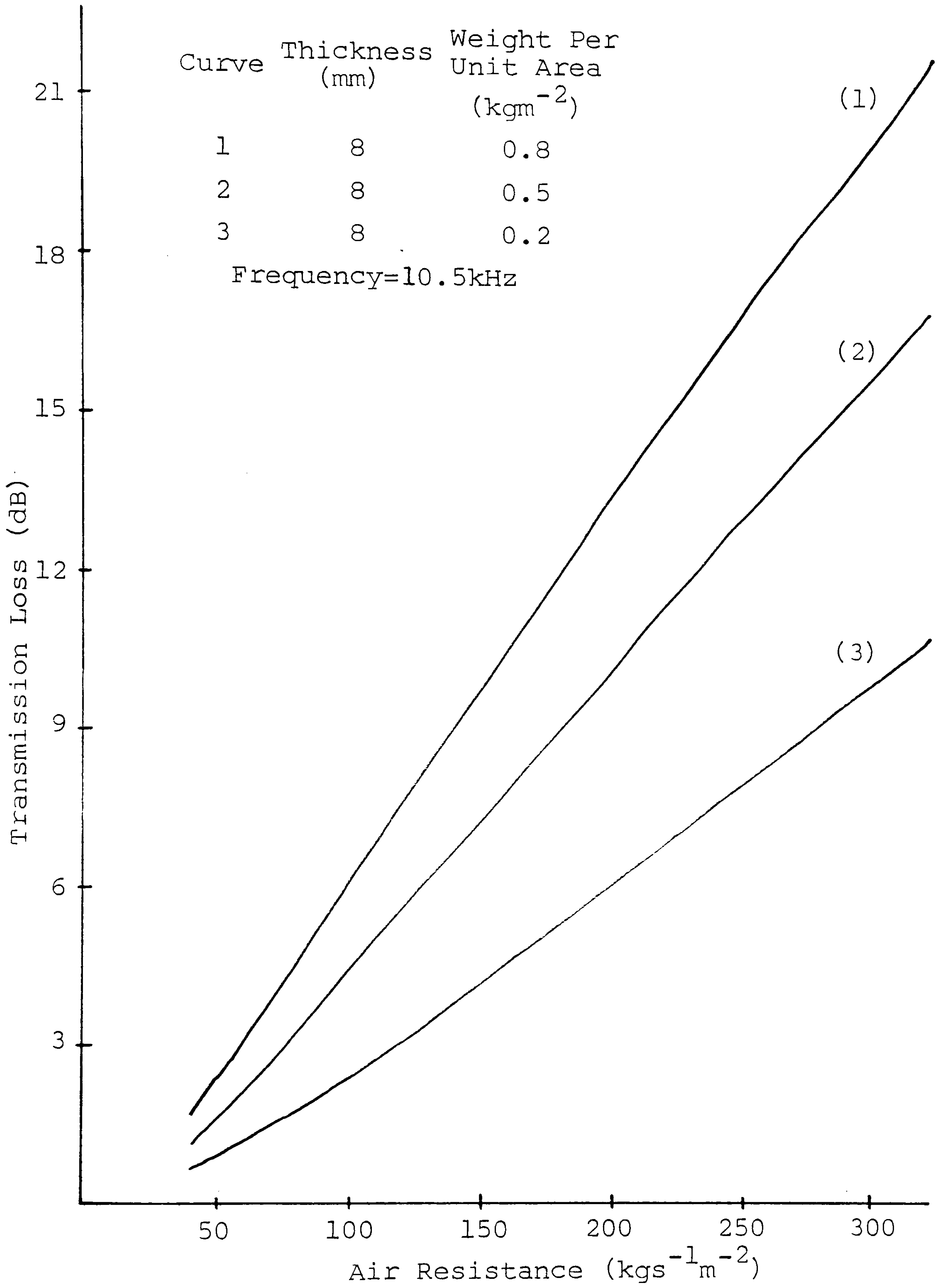


Figure 7.19 Transmission Loss versus air resistance for fabrics of different weight per unit area.

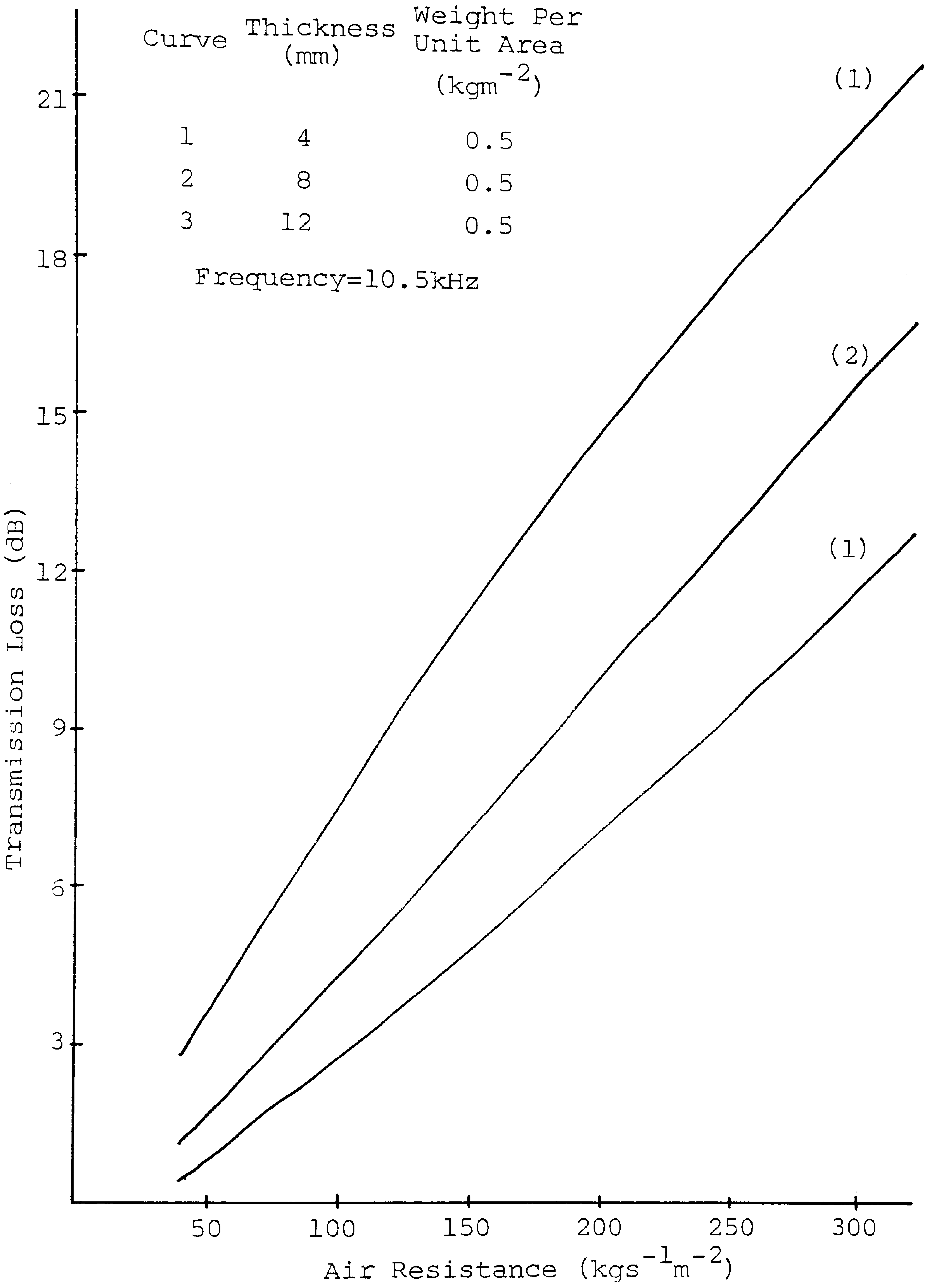


Figure 7.20 Transmission loss versus air resistance for fabrics of different thickness.

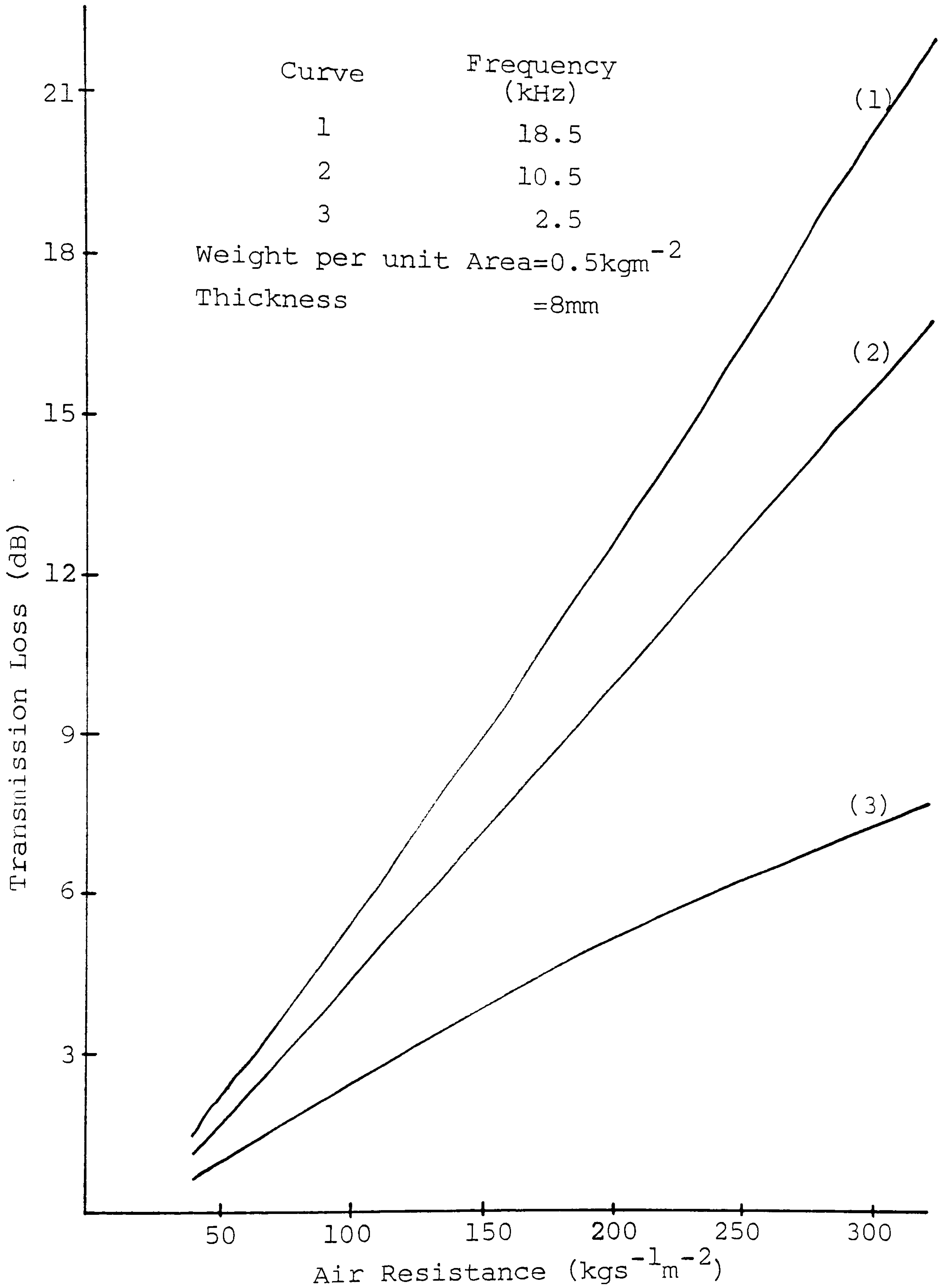


Figure 7.21 Transmission loss versus air resistance at different frequencies.

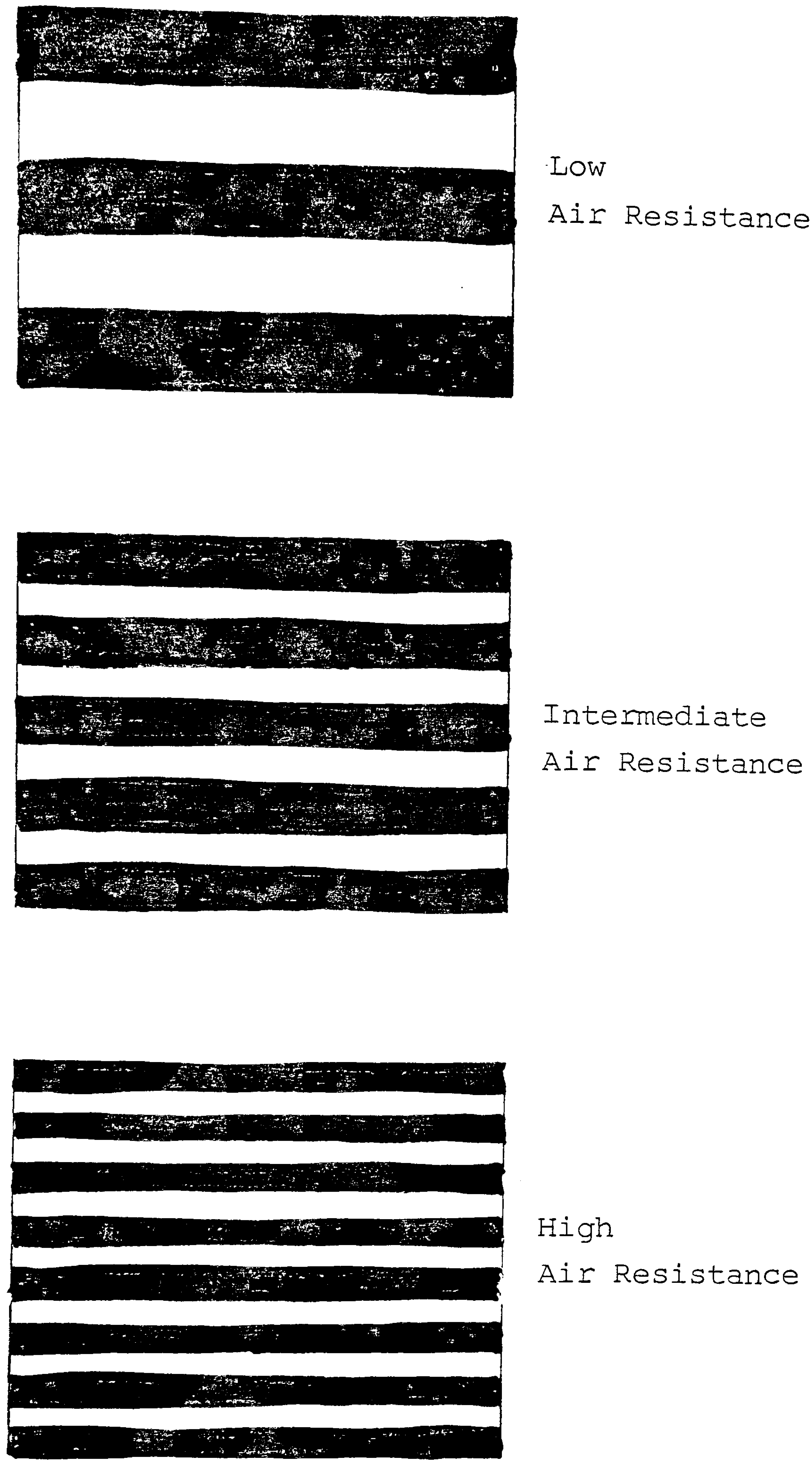


Figure 7.22 Simplified representation of fabrics having same weight per unit area, thickness and porosity but different air resistance.

thickness is a measure of the difficulty associated in blowing unit volume of air per unit area of the fabric per second under a constant pressure differential measured between the two sides of the fabric. Clearly the greater the difficulty, the greater will be the air resistance, and hence the greater will be the energy consumed in moving the air. Hence the transmission loss (which is a measure of the energy consumed) as a consequence of the viscous resistance between the surface of the fibres and air, will increase with increasing air resistance, as the sound wave passes through the fabric. Thus transmission loss will increase with increasing fabric resistance and is in agreement with figures 7.18-7.21.

Figures 7.19 and 7.20 respectively indicates as discussed earlier that for any given value of air resistance, heavier (constant thickness) and thinner (constant weight per unit area) fabrics have higher transmission loss. Also in agreement with the last two sections, figure 7.21 indicates that for all values of air resistance, the transmission loss is greater at high frequencies, and that the increase in transmission loss is greater in going from 2.5kHz to 10.5kHz than in going from 10.5kHz to 19.5kHz.

7.2.4 Effect Of Fibre Density On Transmission Loss

In order to investigate the effect of fibre density on transmission loss, the theoretical equation was applied to a model fabric, as before, in which the fibre density was arbitrarily varied whilst keeping the fabric weight per unit area, thickness and fibre fineness constant. The change in fabric transmission loss as a consequence of the variation in fibre density is indicated in figure 7.23.

The observed decrease in transmission loss with increasing fibre density (at constant weight per unit area, thickness and fibre fineness) can be explained in the following way. As the fibre density increases, the total number of fibres within the fabric will decrease thus increasing the dimensions of the channels within the fabric, consequently producing a decrease in the fabric air resistance. The porosity of the fabric, which is

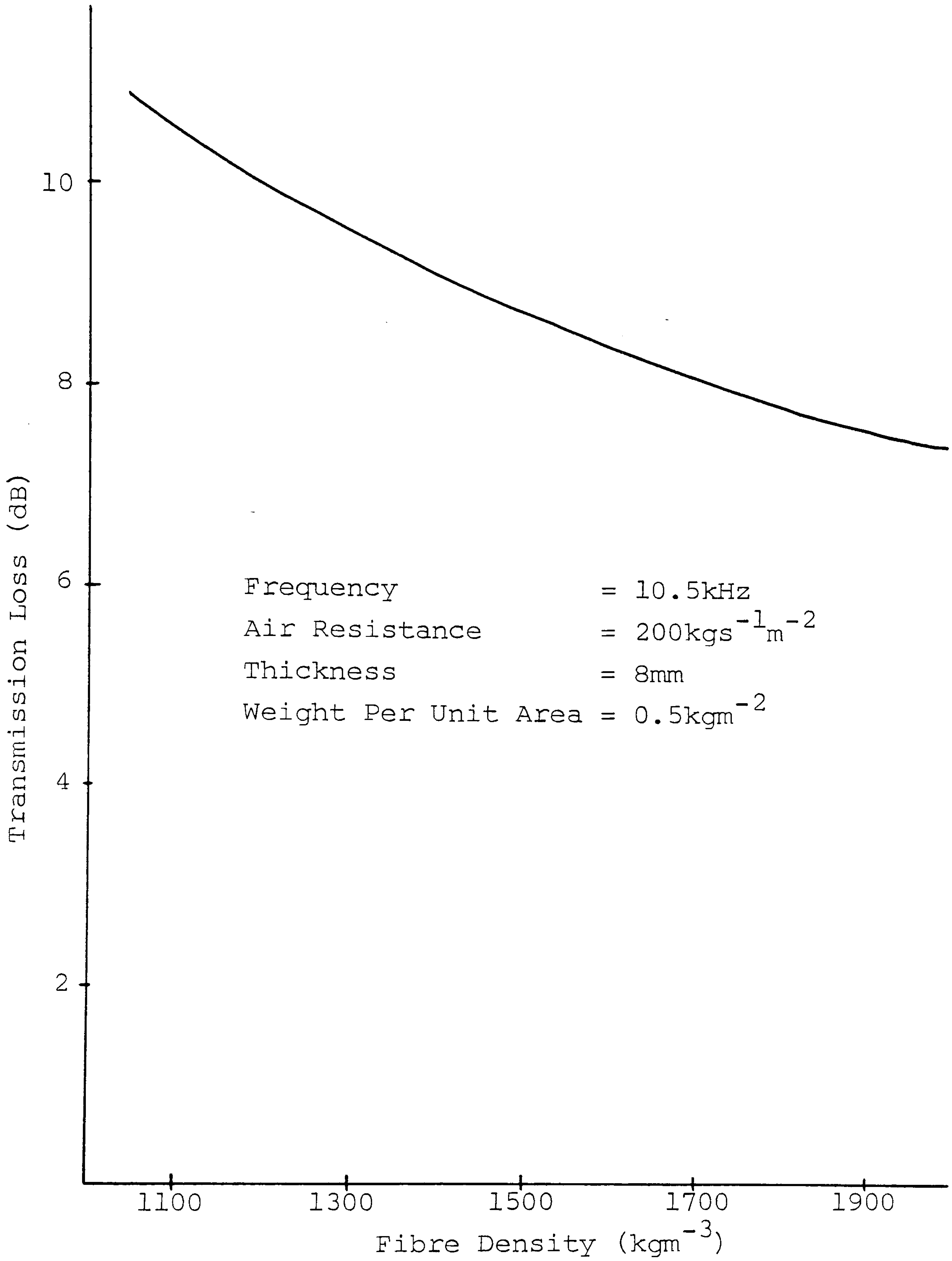


Figure 7.23 Transmission loss versus fibre density.

approximately given by the expression:

$$\text{Porosity} = 1 - \frac{\text{density of the fabric}}{\text{density of the fibre}}$$

is inversely proportional to the fibre density. Hence air resistance obtained from equation 7.1 also will be inversely proportional to the fibre density. As a consequence of this inverse relationship the transmission loss of a fabric of given thickness, weight per unit area and fibre fineness will decrease with fibre density, as indicated in figure 7.23.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Needle-felted fabrics employed in this work are made of fine fibres and are characterised by high porosity. These fabrics by nature of the process by which they are produced, contain fibres which are packed together so as to leave between them many air channels. Consequently it may be concluded that such a fabric placed in the path of a sound wave will absorb sound energy as a consequence of:

(a) friction occuring between the fibres of the material and the air particles passing through the channels in the fabric;

(b) heat generated resulting from the compression and rarefaction of the contained (compressible) fluid transmitted by conduction through the fibre walls; and

(c) vibrations of the fibres and the air contained within the fabric;

with regard to these effects, a theory can be developed to allow the calculation of transmission loss of such fabrics in terms of fabric weight per unit area, thickness, porosity, air resistance and fibre density. Transmission loss computed from this theory after correction (the reasons for which are discussed) compares very well with the experimentally measured transmission loss for fabrics of different parameters. The theory provides a very good basis for the understanding of the transmission loss process, and yields a quantitative method for achieving any transmission loss by changing the different fabric parameters stated. Moreover, the theoretical analysis together with the experimental results allows a number of general conclusions to be made concerning the influence of fabric parameters on transmission loss. Namely:

(1) For a fabric of any parameters the transmission loss increases with the frequency of the sound source.

(2) For a fabric of fixed thickness, air resistance and fibre density, the transmission loss increases with the

weight per unit area of the fabric.

(3) For a fabric of given weight per unit area, air resistance and fibre density, the transmission loss decreases with the thickness of the fabric.

(4) For a fabric of given weight per unit area, thickness and fibre density, the transmission loss increases with the air resistance of the fabric.

(5) For a fabric of given weight per unit area and thickness, the transmission loss decreases with the density of the fibre.

Essentially it can be concluded that any fabric parameter that will change the microstructure of the fabric, regardless of weight per unit area and thickness of the fabric, also will change the transmission loss.

As a consequence of air resistance being one of the significant factors governing the acoustic properties of the fabric, a preliminary investigation was performed to assess the variation of air resistance with fabric and fibre parameters. As a result of this work air resistance was found to be a complex function depending upon a number of simultaneously variable fabric characteristics, namely weight per unit area, thickness, porosity and fibre fineness. From this investigation it was concluded that a considerable variation in air resistance could be achieved by changing the total exposed surface area in the fabric (regardless of fabric weight per unit area and thickness) and by modifying the size of the channels by means of respectively changing the fibre fineness and fabric density.

The transmission loss of needle-felted fabrics is of interest as a basis for the design of loudspeaker covers and noise attenuating partitions. From the theoretical and the experimental work carried out it can be concluded, that the best characteristics required for a loudspeaker cover, where minimum transmission loss is the objective, are low air resistance and high porosity. In reality this equates to low density fabrics made from very coarse fibres. However in the case of attenuating partitions, where high transmission loss is the objective, the requirements are maximum air resistance coupled with low porosity. This suggests that high density fabric made from very fine fibres is the ideal prerequisite.

Any material placed in the path of a sound wave will reflect part of the incident energy, the amount reflected being dependent upon the porosity of the fabric. Clearly, in many cases where the sound source needs to be partitioned off acoustic reflection can be an added advantage. However in situations such as air craft cabins where both low weight and improvement of speech intelligibility are dominant factors, effects of reflected sound energy can be detrimental if high density materials are used. In such situations, problems due to reflection could be minimised by using graduated porosity material. This could be achieved by connecting fabric layers of decreasing porosity towards the rear thus providing a gradual transition, from the medium of sound wave propagation to the attenuating material.

Finally, a significant and not fully appreciated point relates to the misuse of noise attenuating partitions. After a period of installation the question of painting may arise for decorative needs. Such materials often are painted for the purpose of decoration, but clearly this will have an adverse influence upon their sound attenuating properties. These materials owe their characteristic acoustic nature to their porous structure, which will be greatly impaired when coated with oil paint or other materials, since the openings of the channels will become blocked, and consequently the absorbing ability will suffer.

8.2 Recommendations

The technique used for measuring the transmission loss provides a reproducable method of ranking materials according to their ability to transmit sound through them. Although the technique is fairly simple and straight forward. However considerable time was spent on recording and calculating the transmission loss. Future work could be directed towards accelerating this procedure, by using an integrator. The output from the digitrace which is proportional to the sound level could be interrupted and presented to an integrator, to obtain a continuous "point to point" integration of the output voltage. This voltage together with a voltage proportional to the frequency then could be presented to a paper tape punch and a mini computer, from which the area under the transmission loss curve could be obtained.

Future work also could involve a study of the effect of hollow fibres on transmission loss. A fabric of given weight per unit area and thickness made from such fibres should have higher resistance to the flow of air due to the fact that these fibres will have a higher ratio of fibre surface area to fibre weight. Also, these fibres should give higher transmission loss because fabrics made from these fibres will contain two types of channels, namely the channels within the fabric and the channels within the fibres.

Moreover future study could be directed towards the decorative needs, which may be fulfilled by dying the fibres and also blending different coloured fibres. Hence this work could involve a study of the effects of dye stuffs and changing fibre blends. Work also could involve the study of spraying porous fabrics with thin lacquer paints in an attempt to investigate the change in acoustic properties resulting.

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APPENDIX ONE

EXPERIMENTALLY MEASURED TRANSMISSION LOSS

Introduction

This appendix contains the experimentally measured transmission loss as a function of frequency for all fabrics. The results are contained in the form of a table (table A1.1).

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	A1	A2	A3	A4	A5	A6	A7	A8	A9
2.5	0.72	0.72	1.07	1.10	1.09	0.86	0.63	0.92	1.04
3.5	0.82	0.91	1.20	1.32	1.38	1.26	1.12	1.24	1.52
4.5	1.32	1.55	1.81	2.19	2.38	1.93	1.89	2.10	2.30
5.5	0.99	1.23	1.35	1.65	1.84	1.61	1.51	1.70	1.70
6.5	1.11	1.40	1.63	1.96	2.08	1.67	1.64	1.94	2.03
7.5	1.29	1.58	1.68	1.98	2.15	1.96	1.72	2.08	2.18
8.5	1.11	1.32	1.54	1.76	1.96	1.67	1.55	1.76	2.04
9.5	1.31	1.50	1.78	2.13	2.30	2.05	1.79	2.12	2.37
10.5	1.33	1.47	1.77	2.10	2.26	1.92	1.76	1.98	2.22
11.5	1.26	1.50	1.80	2.19	2.42	2.02	1.91	2.13	2.35
12.5	1.55	1.76	2.06	2.35	2.54	2.33	2.09	2.41	2.64
13.5	1.48	1.77	2.00	2.28	2.57	2.16	2.03	2.28	2.60
14.5	1.40	1.72	2.05	2.38	2.61	2.15	2.12	2.35	2.62
15.5	1.46	1.81	2.14	2.54	2.74	2.14	2.14	2.38	2.69
16.5	1.57	1.91	2.20	2.49	2.78	2.28	2.22	2.46	2.83
17.5	1.50	1.78	2.12	2.46	2.74	2.30	2.16	2.38	2.70
18.5	1.45	1.84	2.15	2.53	2.74	2.20	2.17	2.41	2.71
19.5	1.57	1.91	2.14	2.56	2.78	2.50	2.44	2.59	2.78

Table A1.1

FREQUENCY kHz	TRANSMISSION LOSS (dB)									
	FABRIC									
	A10	A11	B1	B2	B3	B4	B5	B6	B7	B8
2.5	1.10	1.36	0.42	0.83	0.77	1.03	1.21	1.51	1.32	1.76
3.5	1.65	1.98	0.38	0.81	0.79	1.10	1.25	1.64	1.38	1.99
4.5	2.51	2.83	0.96	1.52	1.44	1.83	2.18	2.59	2.39	3.04
5.5	2.12	2.33	0.58	1.23	1.10	1.48	1.77	2.08	2.00	2.55
6.5	2.38	2.78	0.64	1.52	1.36	1.88	2.06	2.62	2.34	2.13
7.5	2.50	2.85	0.75	1.55	1.37	1.81	2.05	2.36	2.16	2.79
8.5	2.26	2.62	0.65	1.30	1.29	1.70	2.18	2.49	2.22	3.03
9.5	2.67	3.09	0.79	1.74	1.58	2.12	2.32	2.81	2.66	3.31
10.5	2.52	2.90	0.81	1.55	1.39	1.90	2.15	2.54	2.39	3.18
11.5	2.74	3.20	0.85	1.77	1.58	2.14	2.44	2.92	2.85	3.54
12.5	3.02	3.49	1.06	1.92	1.80	2.34	2.54	3.11	2.97	3.66
13.5	2.94	3.38	0.87	1.89	1.61	2.16	2.53	3.06	2.81	3.76
14.5	2.98	3.44	0.91	2.09	1.76	2.39	2.62	3.17	2.94	3.90
15.5	3.03	3.53	0.97	2.18	1.87	2.42	2.61	3.35	3.05	3.92
16.5	3.02	3.57	0.96	2.14	1.89	2.44	2.73	3.43	3.05	3.95
17.5	2.97	3.63	0.87	1.94	1.74	2.29	2.64	3.29	2.79	3.87
18.5	3.07	3.70	0.95	2.11	1.91	2.44	2.70	3.38	2.98	3.86
19.5	3.28	3.75	0.95	2.01	1.87	2.36	2.63	3.35	3.05	3.95

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	C1	C2	C3	C4	C5	C6	C7	C8	C9
3.5	0.42	0.43	0.73	0.45	0.74	0.92	0.75	1.03	0.55
5.5	0.49	0.58	0.80	0.60	0.82	1.13	0.87	1.23	0.80
7.5	0.74	0.85	1.24	0.98	1.13	1.39	0.98	1.62	1.07
9.5	0.81	0.85	1.22	1.05	1.17	1.54	1.12	1.74	1.16
11.5	0.79	0.82	1.39	1.03	1.12	1.56	1.15	1.76	1.02
13.5	0.83	0.86	1.42	1.00	1.16	1.62	1.27	1.84	1.22
15.5	0.84	1.00	1.53	1.21	1.27	1.77	1.21	1.90	1.37
17.5	0.90	1.02	1.51	1.25	1.27	1.94	1.35	2.00	1.49
19.5	0.98	1.08	1.68	1.28	1.40	1.98	1.45	2.09	1.48

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	C10	C11	C12	C13	C14	C15	C16	C17	C18
3.5	0.96	0.92	1.09	1.23	1.47	0.95	0.64	0.69	1.42
5.5	1.19	1.13	1.18	1.35	1.37	1.15	0.77	0.73	1.67
77.5	1.50	1.44	1.44	1.72	1.64	1.45	1.00	1.08	2.07
9.5	1.73	1.66	1.72	2.06	1.95	1.60	1.09	1.13	2.29
11.5	1.68	1.64	1.81	2.16	1.86	1.55	1.04	1.19	2.41
13.5	1.72	1.72	1.86	2.19	1.94	1.72	1.05	1.17	2.51
15.5	1.88	1.91	2.11	2.42	2.14	1.88	1.19	1.30	2.57
17.5	1.95	1.86	2.21	2.41	2.16	1.95	1.46	1.32	2.69
19.5	1.99	1.98	2.14	2.53	2.37	2.13	1.41	1.50	2.68

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB) FABRIC								
	C19	C20	C21	C22	C23	C24	C25	C26	C27
2.5	0.67	0.76	0.30	0.60	0.43	0.46	0.65	0.76	0.64
4.5	1.44	1.33	0.80	0.61	0.83	0.82	1.73	1.33	1.13
6.5	1.17	1.29	0.66	0.56	0.67	0.80	1.26	1.26	0.90
8.5	1.11	1.16	0.54	0.54	0.59	0.75	1.24	1.10	0.95
10.5	1.29	1.40	0.78	0.76	0.86	0.96	1.46	1.41	1.23
12.5	1.66	1.73	1.00	0.96	0.94	1.22	1.76	1.73	1.40
14.5	1.59	1.59	0.83	0.79	0.83	1.09	1.78	1.58	1.36
16.5	1.73	1.68	0.90	0.96	0.90	1.27	1.85	1.72	1.44
18.5	1.52	1.67	0.98	0.79	0.97	1.08	2.03	1.49	1.30

FREQUENCY kHz	TRANSMISSION LOSS (dB) FABRIC								
	C28	C29	C30	C31	C32	C33	C34	C35	C36
2.5	0.86	0.43	1.06	0.93	1.06	0.63	0.82	1.02	0.97
4.5	1.60	1.17	1.67	1.84	1.88	1.16	1.53	1.94	1.98
6.5	1.52	0.99	1.45	1.59	1.93	0.95	1.56	1.78	1.78
8.5	1.34	0.89	1.33	1.52	1.80	0.92	1.45	1.58	1.70
10.5	1.52	1.14	1.57	1.78	1.98	1.14	1.66	1.78	1.81
12.5	1.89	1.38	2.03	2.10	2.48	1.28	2.06	2.17	2.21
14.5	1.89	1.33	1.89	2.19	2.45	1.37	2.09	2.22	2.19
16.5	2.13	1.59	1.98	2.24	2.57	1.35	2.11	2.35	2.22
18.5	2.10	1.32	1.90	2.10	2.50	1.27	2.03	2.32	2.28

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	D1	D2	D3	D4	D5	D6	D7	E1	E2
2.5	0.56	0.51	0.87	0.85	0.85	1.09	1.33	0.45	0.43
3.5	0.54	0.72	0.79	0.90	1.10	1.28	1.50	0.50	0.49
4.5	0.87	1.18	1.29	1.61	1.89	2.06	2.64	0.73	0.83
5.5	0.82	0.87	1.11	1.37	1.53	1.62	2.01	0.43	0.66
6.5	0.83	1.08	1.27	1.57	1.93	2.01	2.54	0.46	0.71
7.5	0.94	1.16	1.39	1.61	1.85	1.95	2.33	0.49	0.82
8.5	0.71	0.98	1.15	1.38	1.66	1.78	2.26	0.38	0.62
9.5	0.95	1.28	1.61	1.94	2.21	2.35	2.78	0.66	0.93
10.5	0.96	1.11	1.39	1.72	1.87	1.99	2.24	0.70	0.84
11.5	0.89	1.02	1.46	1.79	2.06	2.26	2.57	0.55	0.71
12.5	1.35	1.51	1.90	2.22	2.51	2.72	2.90	0.90	1.20
13.5	1.24	1.27	1.49	1.84	2.18	2.40	2.66	0.63	0.89
14.5	1.22	1.23	1.59	2.02	2.30	2.62	2.90	0.62	0.92
15.5	1.28	1.42	1.81	2.06	2.43	2.05	3.01	0.67	0.99
16.5	1.26	1.48	1.83	2.12	2.44	2.74	3.16	0.65	1.00
17.5	1.20	1.56	1.76	2.05	2.34	2.61	3.05	0.73	0.96
18.5	1.11	1.46	1.71	2.06	2.39	2.65	3.06	0.67	0.96
19.5	1.27	1.70	1.93	2.20	2.51	2.73	3.22	0.80	1.11

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	E3	E4	E5	E6	E7	E8	E9	E10	E11
2.5	0.67	0.52	0.51	0.83	0.65	0.54	0.61	0.80	0.94
3.5	0.60	0.49	0.61	0.78	0.73	0.56	0.50	0.78	0.79
4.5	0.92	0.96	1.16	1.18	1.33	1.17	1.33	1.45	1.42
5.5	0.63	0.65	0.78	0.84	0.89	0.82	0.82	1.08	1.00
6.5	0.73	0.96	0.99	1.01	1.22	1.13	1.13	1.29	1.54
7.5	0.88	0.95	1.05	1.04	1.15	1.21	1.11	1.22	1.33
8.5	0.67	0.85	0.77	1.01	1.05	0.89	1.01	1.27	1.24
9.5	1.21	1.31	1.33	1.50	1.56	1.45	1.68	1.80	1.91
10.5	0.98	1.01	1.02	1.24	1.22	1.21	1.39	1.42	1.40
11.5	0.94	1.10	1.04	1.28	1.39	1.21	1.52	1.63	1.72
12.5	1.44	1.40	1.68	1.76	1.78	1.83	1.92	2.16	1.97
13.5	1.05	1.02	1.42	1.26	1.30	1.35	1.44	1.63	1.54
14.5	1.18	1.13	1.40	1.55	1.63	1.50	1.63	1.96	1.91
15.5	1.33	1.27	1.56	1.62	1.54	1.66	1.78	1.99	2.04
16.5	1.22	1.32	1.44	1.68	1.59	1.59	1.73	2.12	2.00
17.5	1.18	1.12	1.48	1.57	1.46	1.54	1.72	1.98	1.88
18.5	1.13	1.22	1.40	1.67	1.56	1.51	1.60	2.00	2.06
19.5	1.34	1.28	1.55	1.76	1.62	1.71	1.96	2.12	2.16

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)							
	FABRIC							
	E12	F1	F2	F3	F4	F5	F6	G1
2.5	0.93	2.30	2.15	2.59	3.31	3.86	4.68	1.02
3.5	0.58	3.24	3.02	3.88	4.73	5.69	6.56	1.39
4.5	1.20	4.60	4.51	5.73	6.43	7.42	8.53	2.08
5.5	0.96	3.50	3.45	4.54	5.16	6.13	7.19	1.58
6.5	1.38	4.34	4,21	5.55	6.26	7.65	9.14	1.87
7.5	1.29	4.20	4,24	5.53	6.29	7.30	8.21	2.23
8.5	1.13	4.17	3.84	5.32	6.13	7.56	8.92	1.80
9.5	1.95	4.70	4.54	6.06	6.99	8.31	9.96	2.10
10.5	1.50	4.50	4.32	5.80	6.58	7.84	9.63	2.07
11.5	1.65	4.70	4.59	6.23	7.08	8.70	10.44	2.09
12.5	2.15	4.91	4.74	6.58	7.39	8.75	10.78	2.32
13.5	1.61	5.01	4.93	6.77	7.62	9.08	10.93	2.21
14.5	1.79	5.07	4.90	6.91	7.61	9.21	11.17	2.12
15.5	2.12	5.35	5.04	6.89	7.69	9.20	11.29	2.33
16.5	2.04	5.40	5.21	7.13	7.92	9.36	11.48	2.45
17.5	1.95	5.15	4.92	6.78	7.87	9.45	11.41	2.24
18.5	1.98	5.52	5.26	7.08	8.16	9.38	11.63	2.28
19.5	2.23	5.47	5.34	7.13	8.18	9.37	11.86	2.45

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	G2	G3	G4	G5	G6	G7	G8	G9	G10
2.5	1.14	1.18	1.30	1.71	1.75	2.19	2.21	2.13	2.65
3.5	1.29	1.64	1.74	2.14	2.74	2.79	3.10	2.95	3.53
4.5	2.01	2.39	2.70	3.20	3.94	3.96	4.31	4.21	4.86
5.5	1.52	1.72	2.11	2.54	2.99	3.20	3.31	3.25	3.91
6.5	1.83	2.16	2.65	3.21	3.80	4.03	4.14	4.29	5.14
7.5	2.17	2.38	2.79	3.15	3.83	3.98	4.20	4.15	4.86
8.5	1.88	2.22	2.55	3.03	3.77	3.98	3.94	4.24	4.87
9.5	2.16	2.56	2.93	3.61	4.19	4.47	4.49	4.69	5.45
10.5	2.12	2.53	2.81	3.32	4.05	4.32	4.25	4.45	5.07
11.5	1.99	2.57	3.09	3.67	4.40	4.59	4.46	4.91	5.64
12.5	2.28	2.76	3.27	3.77	4.58	4.70	4.68	5.07	5.65
13.5	2.20	2.84	3.20	3.73	4.54	4.77	4.70	5.17	5.77
14.5	2.10	2.89	3.11	3.73	4.54	4.87	4.86	5.33	5.95
15.5	2.32	3.02	3.39	3.92	4.72	4.96	4.92	5.36	6.01
16.5	2.43	3.19	3.60	4.05	4.85	5.13	5.15	5.68	6.24
17.5	2.23	3.01	3.35	3.83	4.61	5.10	4.97	5.46	6.02
18.5	2.23	3.03	3.43	3.95	4.75	5.16	5.11	5.63	6.23
19.5	2.43	3.06	3.70	4.04	4.92	5.24	5.15	5.65	6.26

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)							
	FABRIC							
	G11	G12	G13	G14	H1	H2	H3	H4
2.5	3.28	3.44	3.59	5.85	1.15	1.52	1.83	1.41
3.5	4.81	4.85	5.06	8.16	1.43	2.19	2.72	1.82
4.5	6.25	6.41	6.80	10.20	2.28	3.17	3.86	2.82
5.5	5.36	5.43	5.51	9.34	1.73	2.33	3.02	2.06
6.5	6.48	6.82	7.07	11.30	2.24	2.83	3.76	2.63
7.5	6.07	6.36	6.6	10.36	2.39	2.82	3.64	2.71
8.5	6.54	6.73	6.97	11.27	1.96	2.60	3.64	2.47
9.5	7.13	7.38	7.74	12.05	2.52	3.10	4.12	3.01
10.5	6.90	7.07	7.26	12.21	2.32	2.95	3.92	2.76
11.5	7.67	8.01	8.07	13.22	2.59	3.17	4.30	2.97
12.5	7.64	7.96	7.96	13.26	2,60	3.25	4.39	2.92
13.5	8.06	8.25	8.22	13.95	2.51	3.32	4.49	2.96
14.5	8.19	8.54	8.39	14.50	2.63	3.41	4.67	3.06
15.5	8.23	8.60	8.45	14.57	2.80	3.41	4.68	3.31
16.5	8.42	8.76	8.95	14.85	2.87	3.43	4.80	3.41
17.5	8.53	8.83	8.65	15.06	2.60	3.22	4.68	3.09
18.5	8.51	8.92	9.00	15.04	2.73	3.43	4.90	3.26
19.5	8.67	8.94	9.04	15.25	2.77	3.40	4.80	3.26

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	H5	H6	H7	I1	I2	I3	I4	I5	I6
2.5	2.04	2.18	2.84	0.86	0.77	1.04	1.14	1.19	1.50
3.5	2.73	2.76	3.98	0.98	1.00	1.28	1.49	1.51	2.00
4.5	3.88	4.10	5.11	1.44	1.46	1.86	2.08	2.10	2.73
5.5	3.02	3.33	4,24	1.07	1.18	1.53	1.60	1.62	2.05
6.5	3.59	4.08	5.05	1.31	1.50	2.01	2.09	2.17	2.68
7.5	3.38	3.88	4.65	1.47	1.55	1.96	2.01	2.06	2.43
8.5	3.40	3.91	4.96	1.26	1.26	1.82	1.92	2.02	2.52
9.5	3.81	4.30	5.34	1.68	1.74	2.26	2.40	2.42	2.95
10.5	3.64	4.08	5.17	1.53	1.55	2.01	2.20	2.13	2.74
11.5	4.05	4.49	5.63	1.62	1.75	2.36	2.45	2.42	3.14
12.5	4.13	4.56	5.64	1.81	1.85	2.41	2.56	2.57	3.21
13.5	4.18	4.65	5.99	1.73	1.77	2.37	2.59	2.61	3.30
14.5	4.31	4.75	6.02	1.73	1.80	2.45	2.60	2.70	3.37
15.5	4.35	4.83	6.08	1.68	1.78	2.35	2.50	2.60	3.22
16.5	4.44	4.98	6.27	1.73	1.79	2.48	2.63	2.68	3.33
17.5	4.33	4.80	6.24	1.60	1.64	2.23	2.51	2.58	3.33
18.5	4.50	4.96	6.35	1.82	1.91	2.53	2.66	2.84	3.53
19.5	4.49	5.00	6.46	1.72	1.82	2.46	2.59	2.71	3.41

<u>Table A1.1</u> (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	I7	I8	J1	J2	J3	J4	J5	J6	J7
2.5	1.35	1.95	0.37	0.50	0.44	0.58	0.66	0.89	0.80
3.5	1.92	2.55	0.38	0.62	0.44	0.81	0.91	0.84	0.92
4.5	2.54	3.42	0.78	1.04	0.94	1.23	1.34	1.39	1.33
5.5	1.95	2.84	0.47	0.65	0.55	0.87	1.04	1.03	0.84
6.5	2.55	3.55	0.65	0.86	0.82	1.18	1.35	1.49	1.37
7.5	2.31	3.13	0.79	0.92	0.84	1.23	1.28	1.45	1.21
8.5	2.42	3.37	0.48	0.76	0.74	1.04	1.16	1.32	1.22
9.5	2.69	3.65	0.83	1.04	0.99	1.41	1.50	1.79	1.53
10.5	2.55	3.59	0.78	0.96	0.87	1.22	1.41	1.53	1.42
11.5	2.86	3.94	0.79	1.03	0.91	1.37	1.60	1.77	1.58
12.5	2.96	3.92	1.00	1.27	1.06	1.55	1.66	1.95	1.74
13.5	3.10	4.27	0.85	1.18	0.98	1.43	1.58	1.82	1.61
14.5	3.21	4.37	0.91	1.18	0.95	1.54	1.73	2.01	1.79
15.5	3.03	4.32	0.93	1.16	1.03	1.47	1.72	2.07	1.94
16.5	3.24	4.39	0.92	1.20	1.05	1.60	1.84	2.12	1.96
17.5	3.25	4.43	0.92	1.23	1.06	1.50	1.63	1.93	1.74
18.5	3.43	4.51	0.92	1.30	1.10	1.61	1.88	2.14	1.88
19.5	3.36	4.66	0.93	1.24	1.10	1.54	1.73	2.07	1.77

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)								
	FABRIC								
	J8	J9	J10	J11	J12	J13	J14	J15	K1
2.5	0.81	1.10	1.06	1.14	1.13	1.25	1.46	1.22	0.56
3.5	1.00	1.16	1.42	1.53	1.55	1.63	1.75	1.63	0.77
4.5	1.70	1.86	2.17	2.15	2.17	2.26	2.52	2.41	1.17
5.5	1.20	1.31	1.57	1.54	1.66	1.67	1.84	1.62	0.66
6.5	1.55	1.83	2.15	2.15	2.23	2.30	2.51	2.24	1.05
7.5	1.36	1.77	1.96	1.97	1.97	2.13	2.29	2.21	0.96
8.5	1.35	1.64	1.95	2.07	1.94	2.26	2.33	2.19	0.95
9.5	1.74	2.02	2.35	2.26	2.33	2.50	2.73	2.60	1.34
10.5	1.54	1.76	2.02	2.16	2.06	2.45	2.43	2.26	1.07
11.5	1.82	2.13	2.46	2.52	2.48	2.70	2.81	2.70	1.14
12.5	1.90	2.16	2.35	2.52	2.37	2.71	2.79	2.73	1.40
13.5	1.92	2.04	2.40	2.60	2.43	2.80	2.86	2.73	1.29
14.5	1.99	2.19	2.44	2.48	2.57	2.77	2.88	2.86	1.43
15.5	1.99	2.31	2.48	2.56	2.55	2.89	2.89	2.82	1.32
16.5	2.02	2.36	2.62	2.68	2.71	2.99	3.09	2.96	1.40
17.5	1.86	2.16	2.43	2.58	2.57	2.94	2.91	2.84	1.35
18.5	2.06	2.31	2.62	2.62	2.58	2.88	3.02	2.91	1.54
19.5	2.00	2.22	2.55	2.63	2.61	2.99	3.07	2.88	1.42

Table A1.1 (continued)

FREQUENCY kHZ	TRANSMISSION LOSS (dB)							
	FABRIC							
	K2	K3	K4	K5	K6	K7	K8	K9
2.5	0.54	1.01	1.07	1.12	0.99	1.20	1.21	1.13
3.5	0.95	1.07	1.30	1.31	1.22	1.52	1.58	1.43
4.5	1.34	1.57	1.92	1.99	1.98	2.23	2.28	2.25
5.5	0.91	1.13	1.33	1.46	1.47	1.48	1.65	1.48
6.5	1.38	1.75	2.02	2.21	2.13	2.35	2.36	2.24
7.5	1.17	1.49	1.68	1.80	1.81	1.97	1.88	2.07
8.5	1.27	1.48	1.70	1.91	1.87	2.01	2.23	2.10
9.5	1.61	1.92	2.13	2.28	2.21	2.30	2.45	2.43
10.5	1.36	1.51	1.74	1.94	1.87	1.99	2.15	2.06
11.5	1.55	1.92	2.29	2.47	2.38	2.42	2.60	2.56
12.5	1.62	2.01	2.18	2.33	2.30	2.28	2.45	2.48
13.5	1.51	1.96	2.32	2.41	2.37	2.50	2.62	2.65
14.5	1.55	2.11	2.39	2.50	2.50	2.53	2.70	2.84
15.5	1.61	1.97	2.30	2.47	2.41	2.44	2.69	2.87
16.5	1.73	2.13	2.49	2.56	2.58	2.57	2.78	3.09
17.5	1.70	2.03	2.36	2.56	2.49	2.54	2.79	2.91
18.5	1.88	2.12	2.53	2.67	2.63	2.73	2.92	3.14
19.5	1.77	2.04	2.40	2.59	2.56	2,68	2.89	3.06

Table A1.1 (continued)

FREQUENCY kHz	TRANSMISSION LOSS (dB)							
	FABRIC							
	L1	L2	L3	L4	L5	L6	L7	L8
2.5	0.32	0.56	0.65	0.78	0.99	1.21	1.32	1.50
3.5	0.46	0.65	0.70	0.97	1.33	1.40	1.94	2.10
4.5	0.84	1.01	0.97	1.40	1.77	2.02	2.60	2.81
5.5	0.57	0.77	0.88	1.08	1.35	1.62	2.21	2.40
6.5	0.68	0.93	1.05	1.32	1.79	2.12	2.79	2.93
7.5	0.62	0.91	1.07	1.30	1.63	2.01	2.44	2.55
8.5	0.66	0.92	0.89	1.26	1.73	1.93	2.54	2.65
9.5	0.84	0.95	1.18	1.53	2.09	2.26	2.92	3.04
10.5	0.77	1.03	1.08	1.33	1.85	1.95	2.71	2.84
11.5	0.87	1.16	1.21	1.49	2.17	2.66	3.12	3.26
12.5	1.01	1.26	1.42	1.66	2.24	2.51	3.04	3.24
13.5	0.91	1.20	1.20	1.50	2.11	2.43	3.07	3.28
14.5	0.92	1.25	1.29	1.55	2.21	2.48	3.16	3.27
15.5	0.98	1.34	1.48	1.59	2.26	2.70	3.28	3.52
16.5	1.02	1.27	1.55	1.74	2.49	2.83	3.35	3.56
17.5	0.98	1.12	1.50	1.74	2.37	2.77	3.28	3.45
18.5	0.94	1.26	1.51	1.69	2.37	2.86	3.37	3.43
19.5	0.95	1.15	1.44	1.66	2.25	2.81	3.38	3.64

Table A1.1 (continued)

APPENDIX TWO

COMPARISON BETWEEN EXPERIMENTAL AND CORRECTED THEORETICAL TRANSMISSION LOSS

Introduction

This appendix shows the comparison between experimental and corrected theoretical transmission loss for all fabric as discussed in chapter six, section two.

Throughout this appendix the following nomenclature is used:

⊙	Experimentally measured transmission loss.
———	Theoretically (corrected) calculated transmission loss.

Figure A2.1 Experimental and theoretical transmission loss versus frequency for fabric A1.

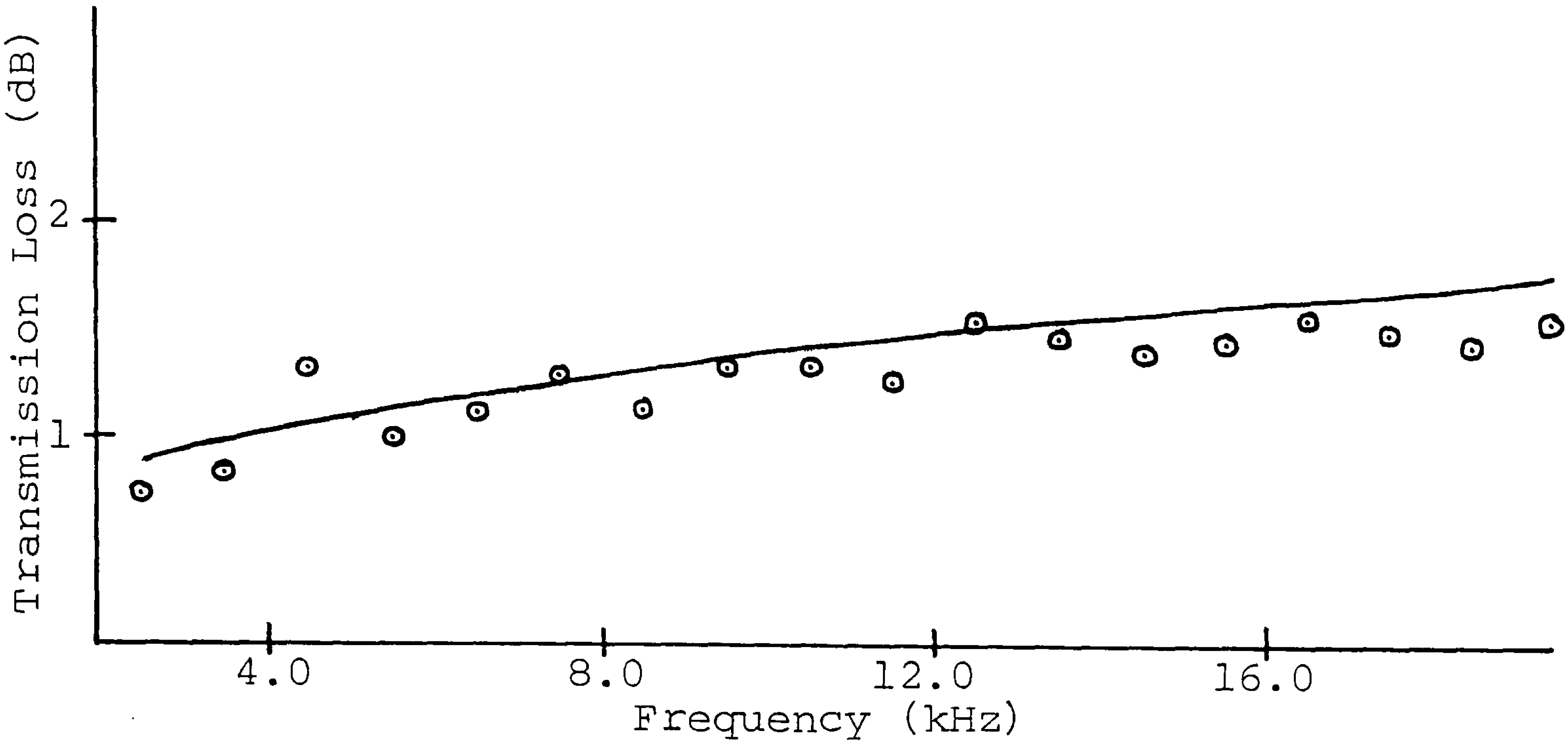


Figure A2.2 Experimental and theoretical transmission loss versus frequency for fabric A2.

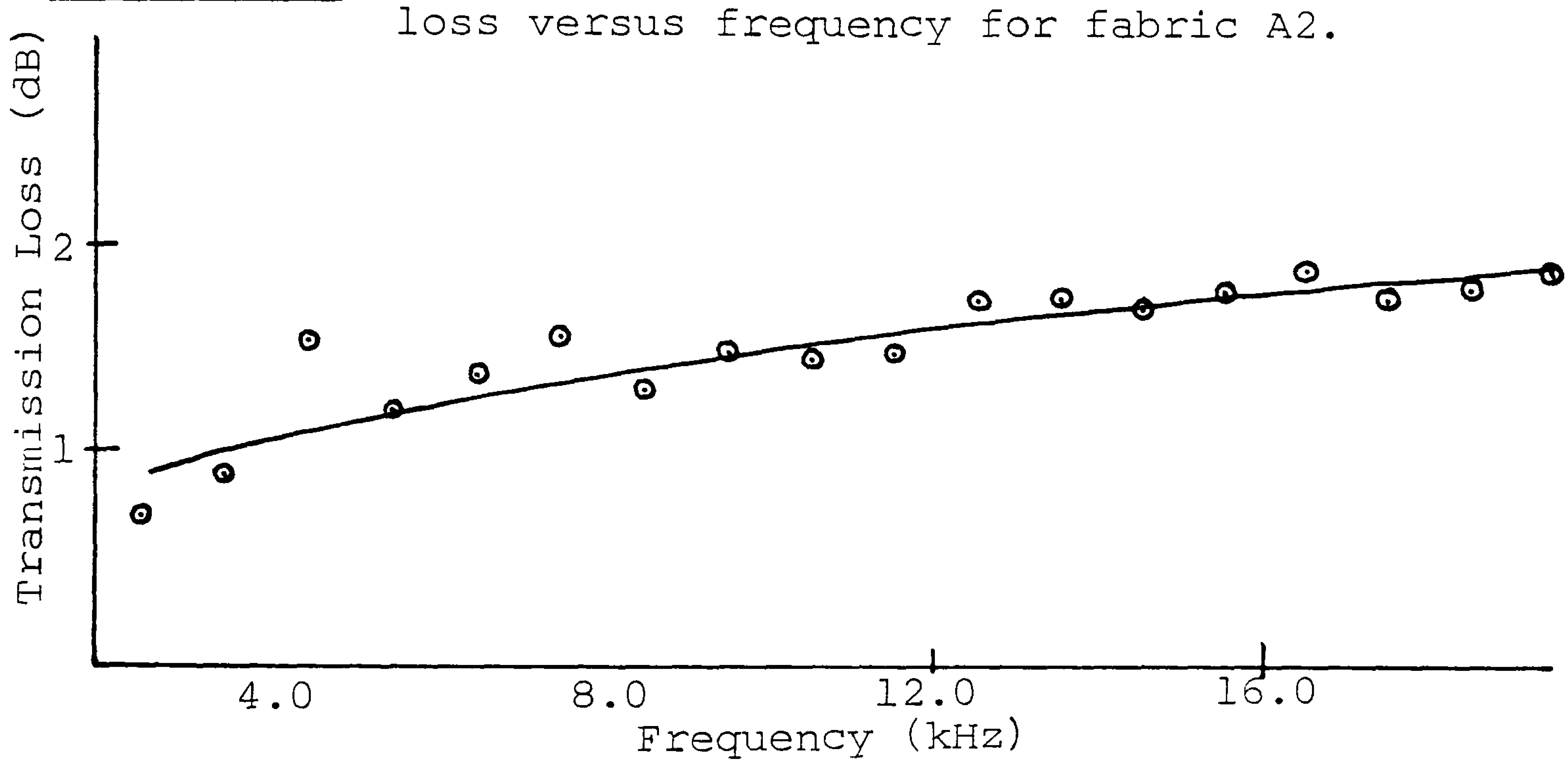


Figure A2.3 Experimental and theoretical transmission loss versus frequency for fabric A3.

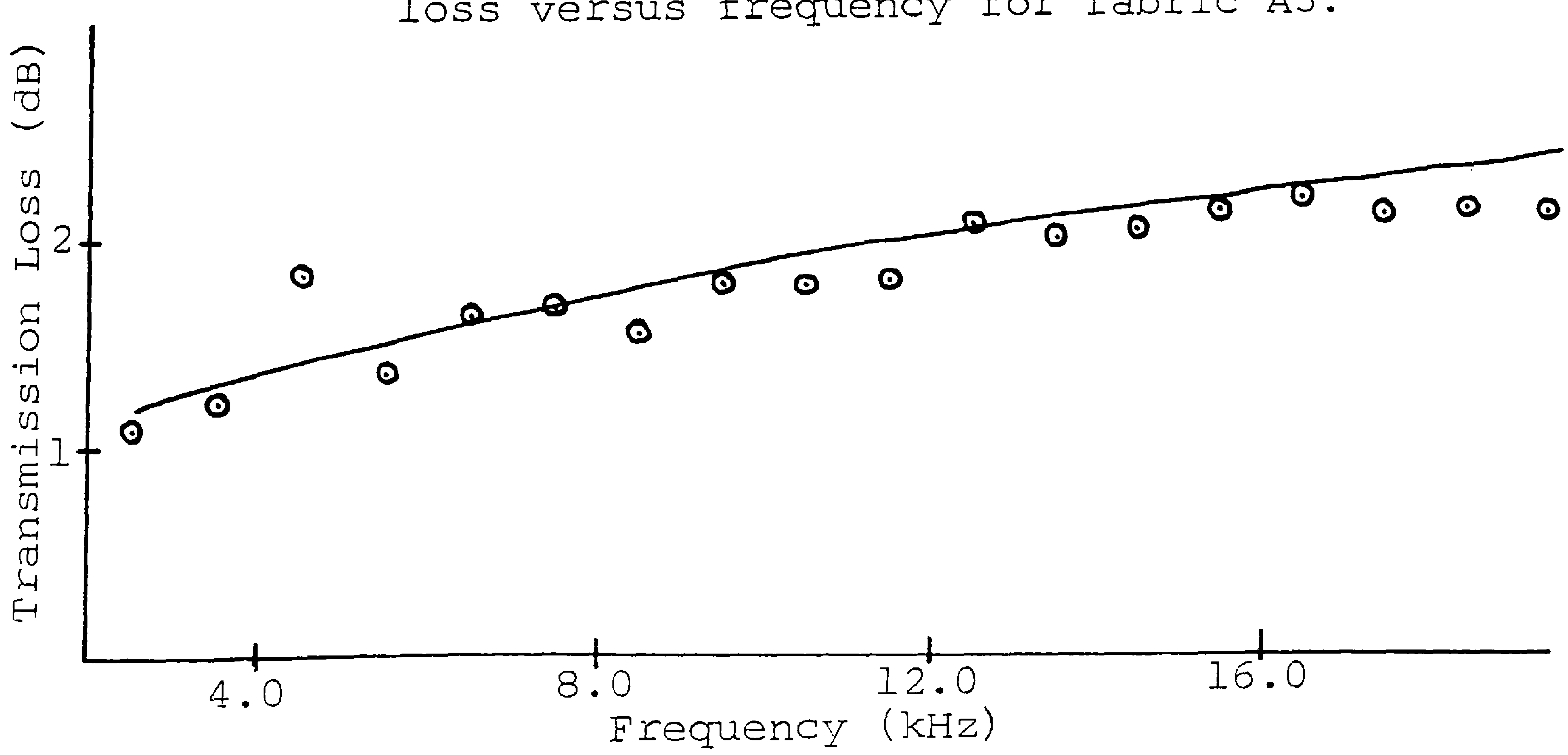


Figure A2.4 Experimental and theoretical transmission loss versus frequency for fabric A4.

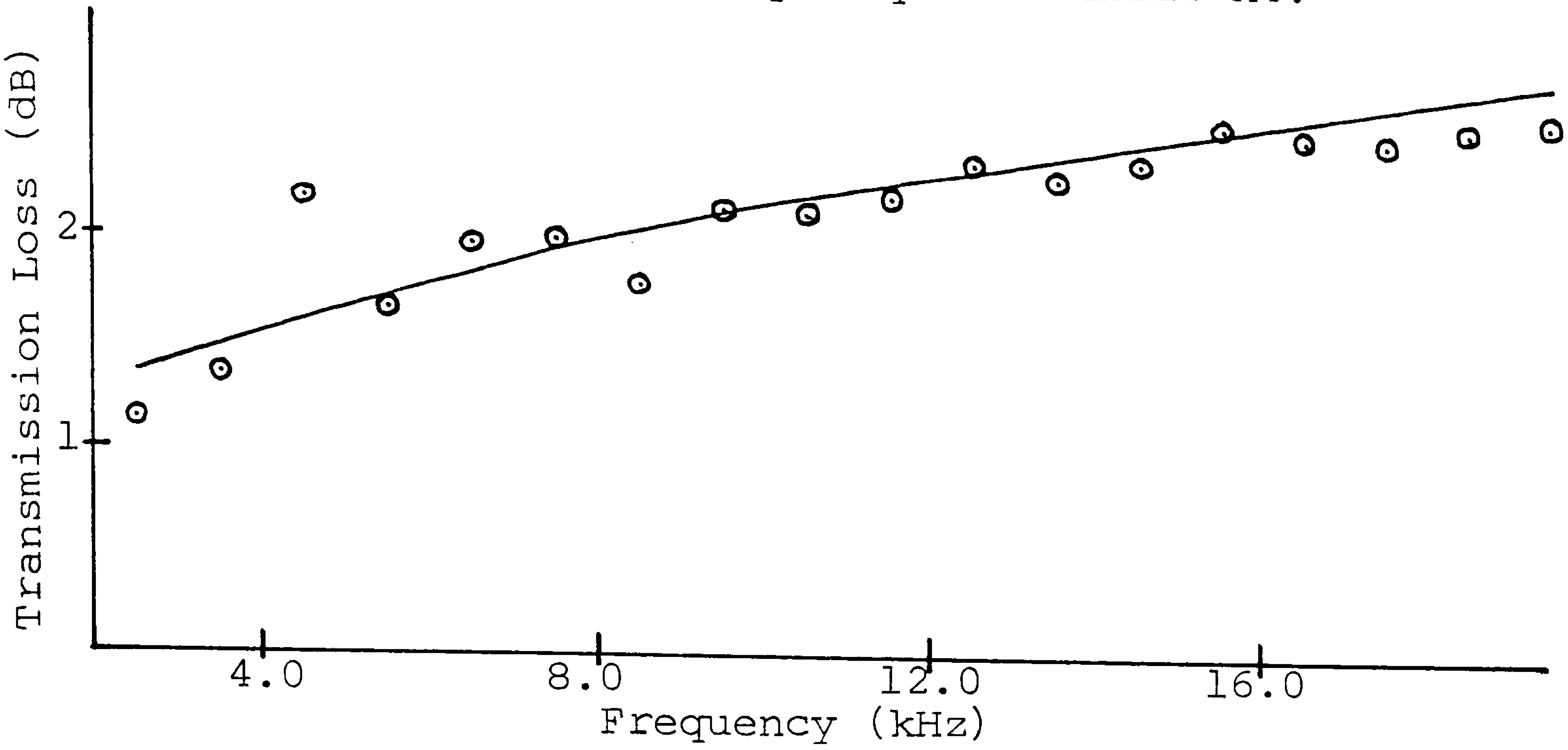


Figure A2.5 Experimental and theoretical transmission loss versus frequency for fabric A5.

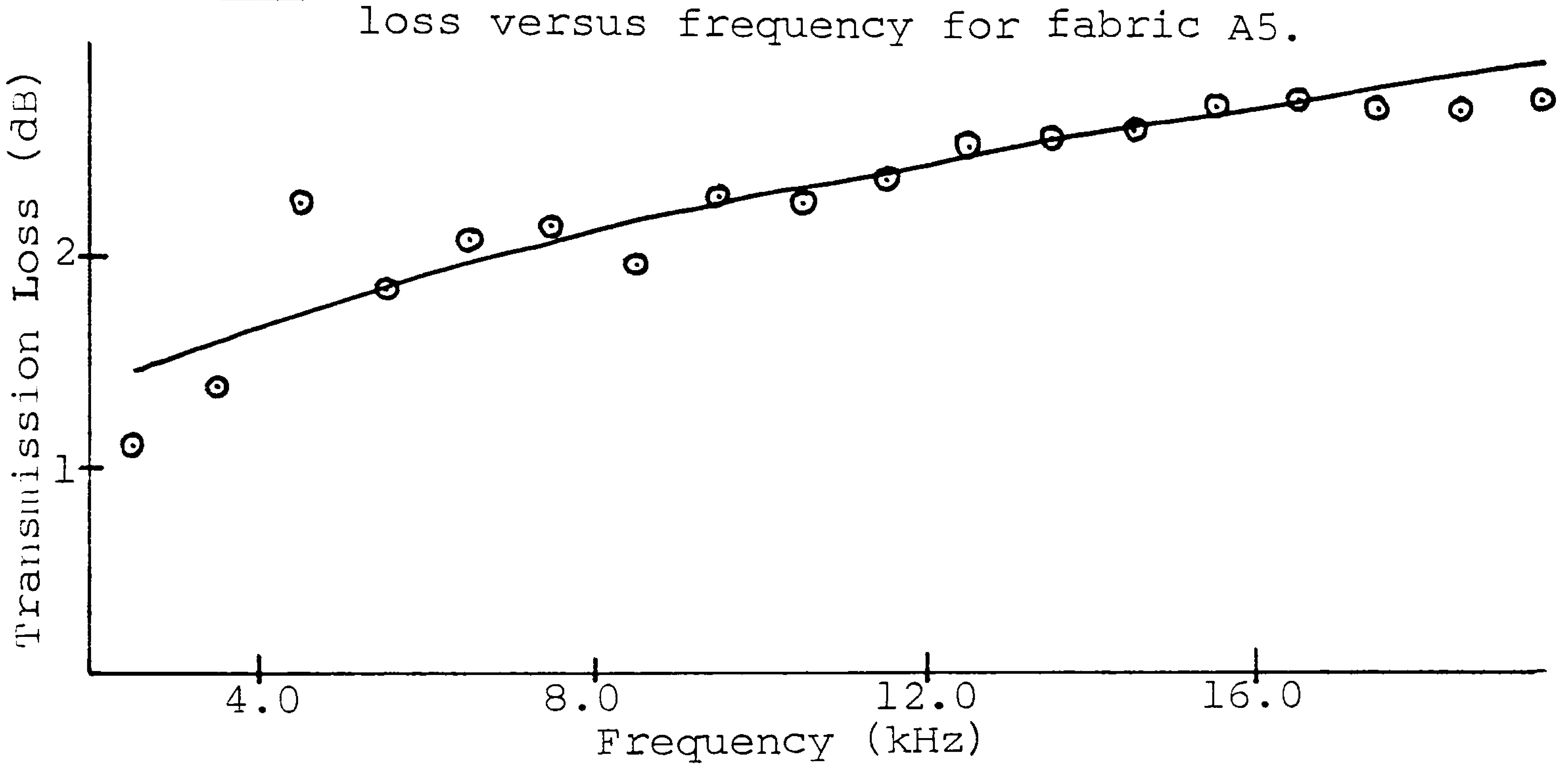


Figure A2.6 Experimental and theoretical transmission loss versus frequency for fabric A6.

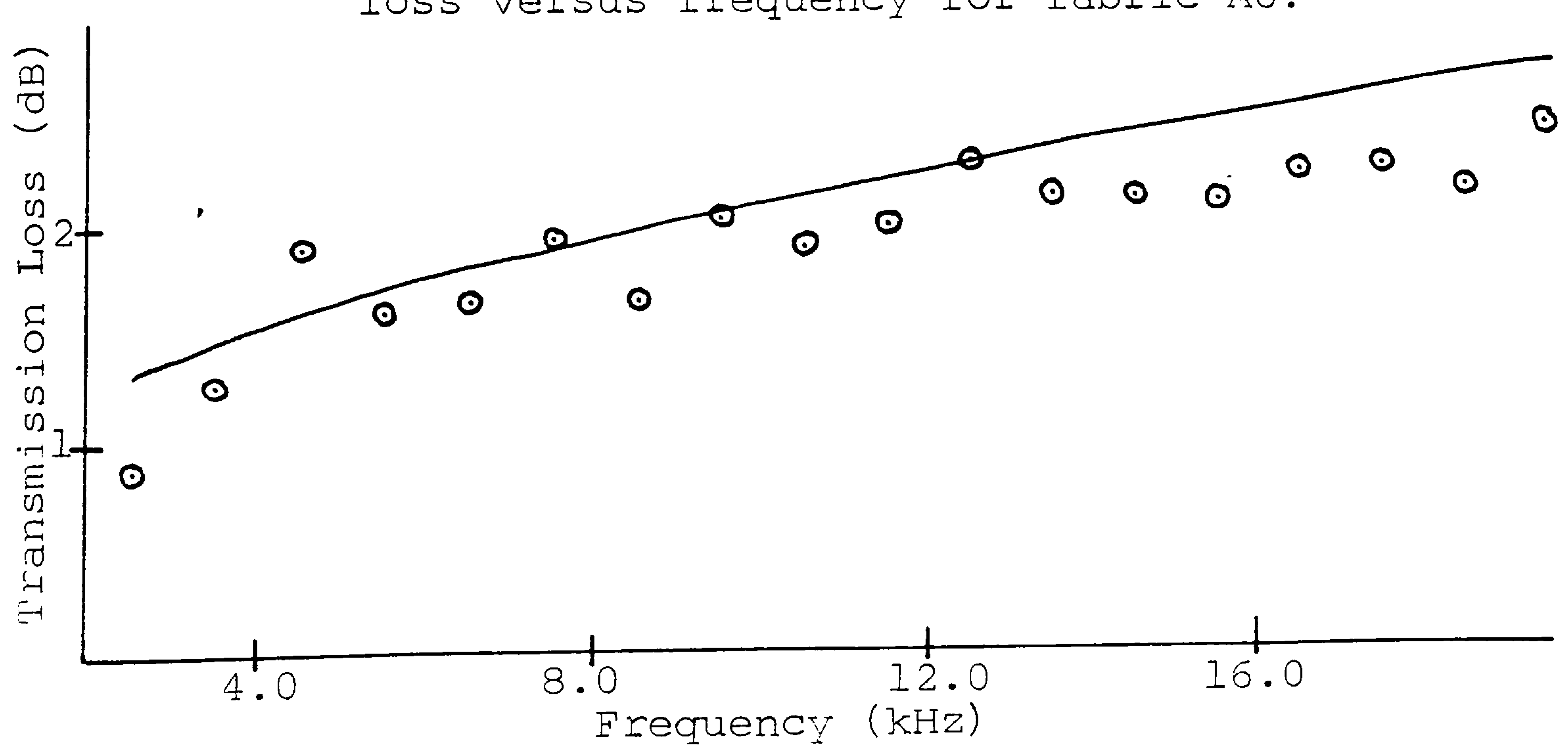


Figure A2.7 Experimental and theoretical transmission loss versus frequency for fabric A7.

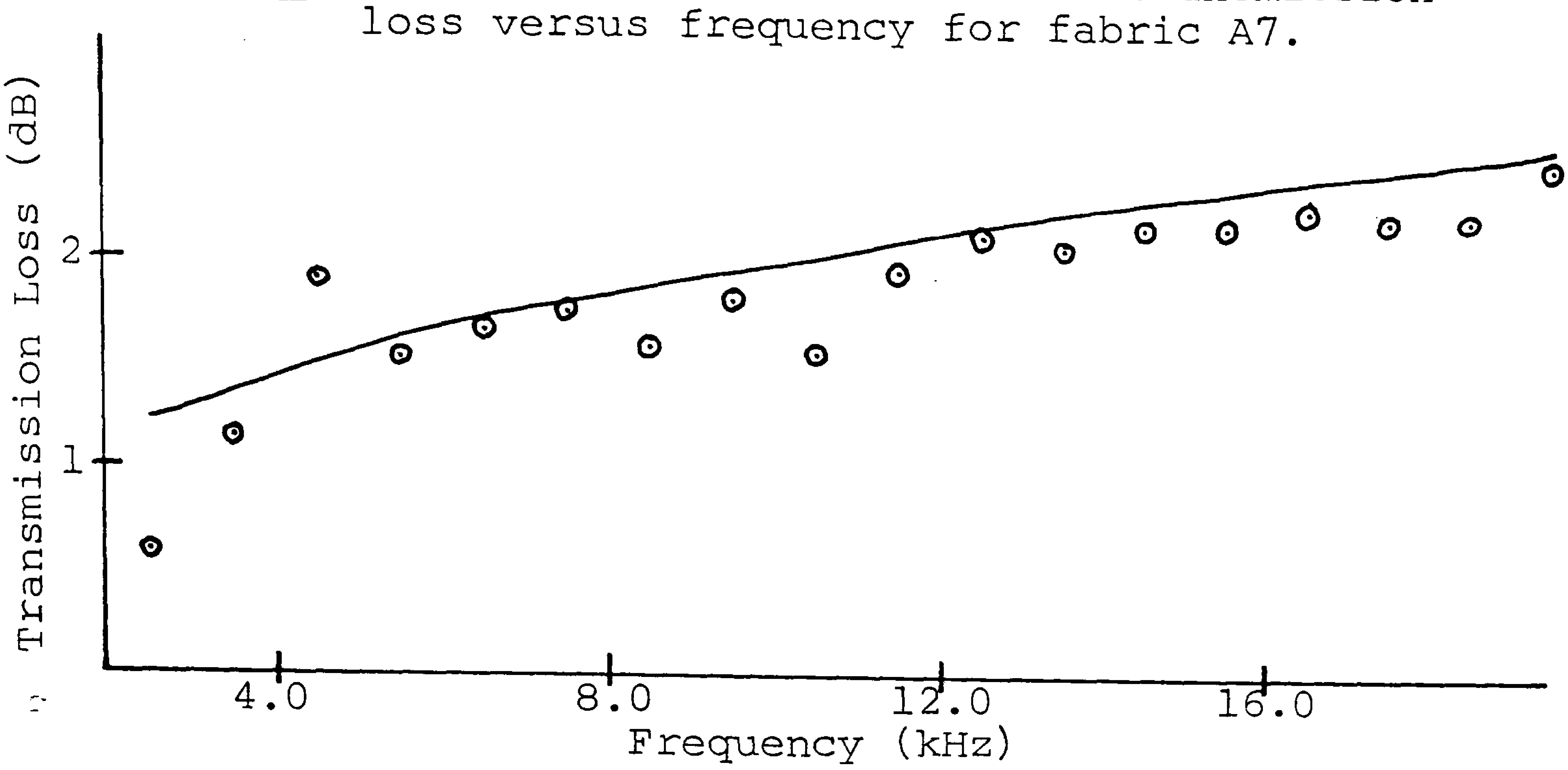


Figure A2.8 Experimental and theoretical transmission loss versus frequency for fabric A8.

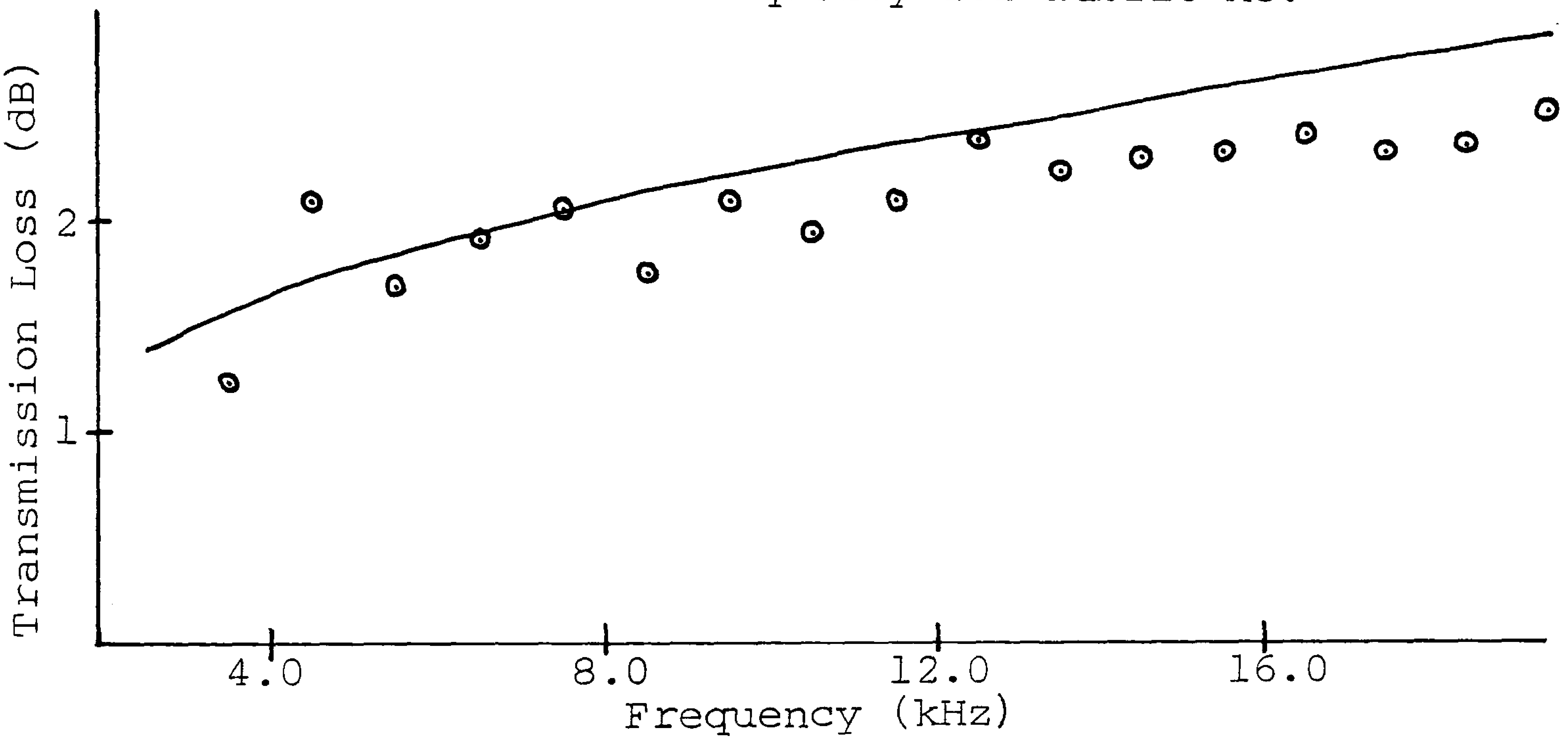


Figure A2.9 Experimental and theoretical transmission loss versus frequency for fabric A9.

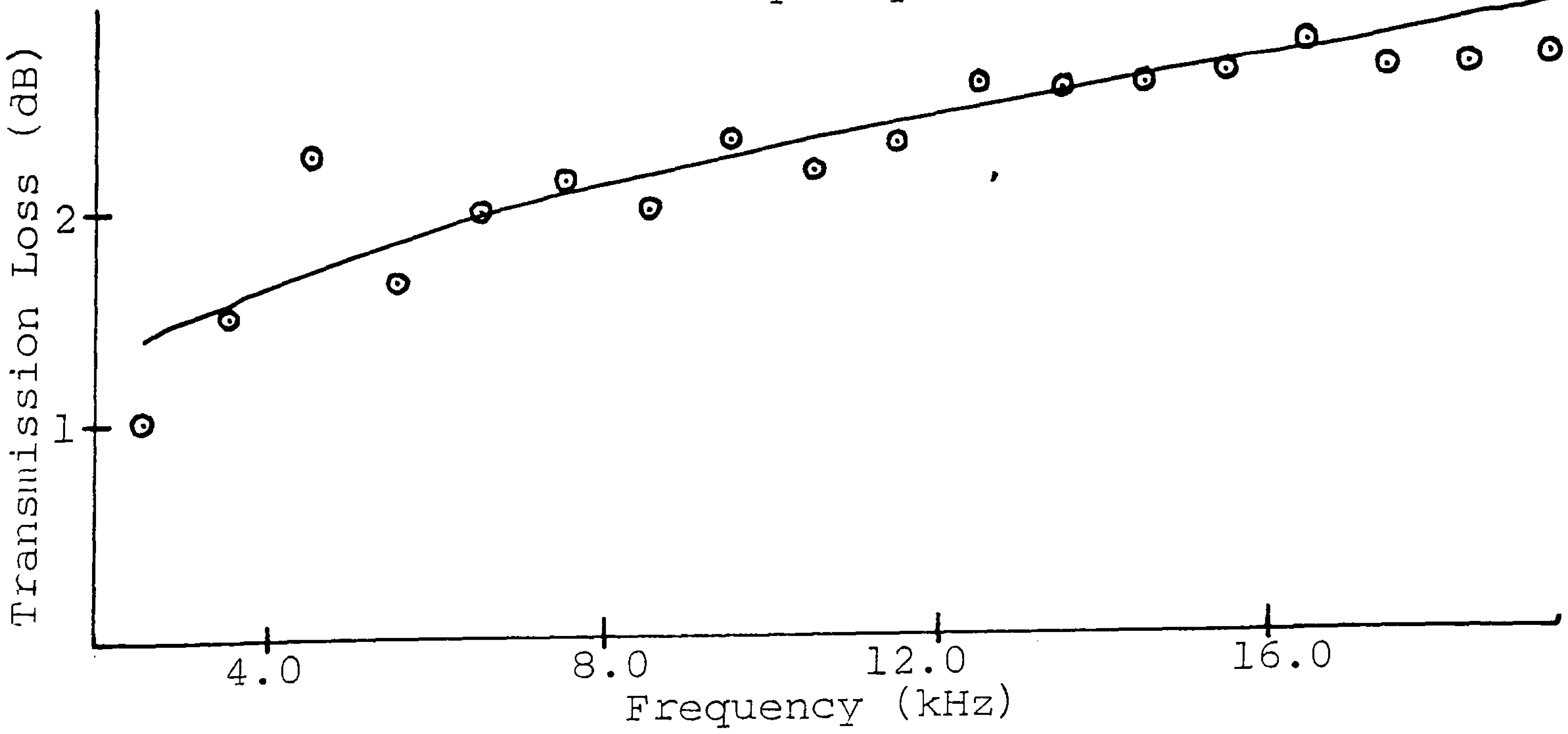


Figure A2.10 Experimental and theoretical transmission loss versus frequency for fabric A10.

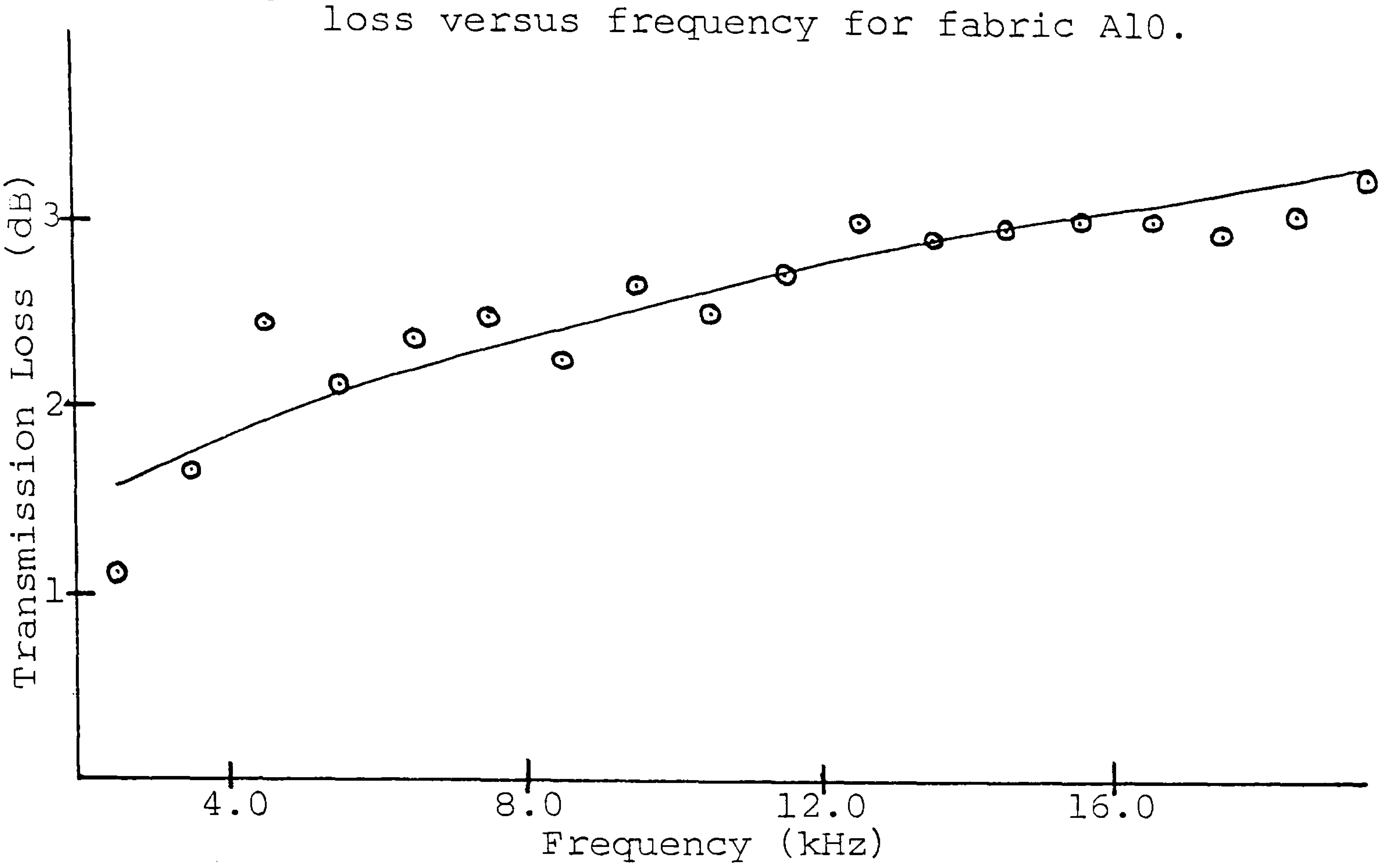


Figure A2.11 Experimental and theoretical transmission loss versus frequency for fabric A11.

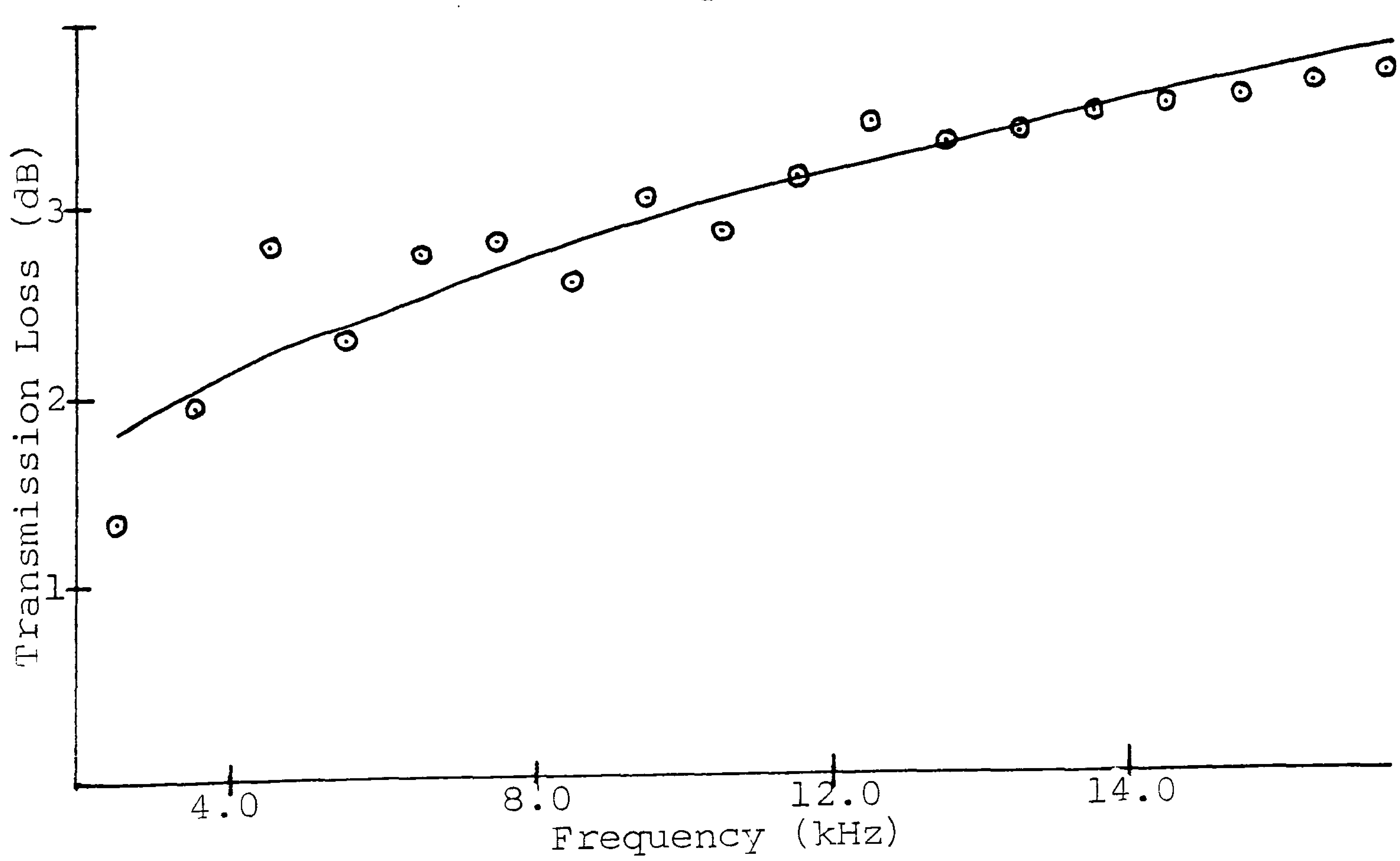


Figure A2.12 Experimental and theoretical transmission loss versus frequency for fabric B1.

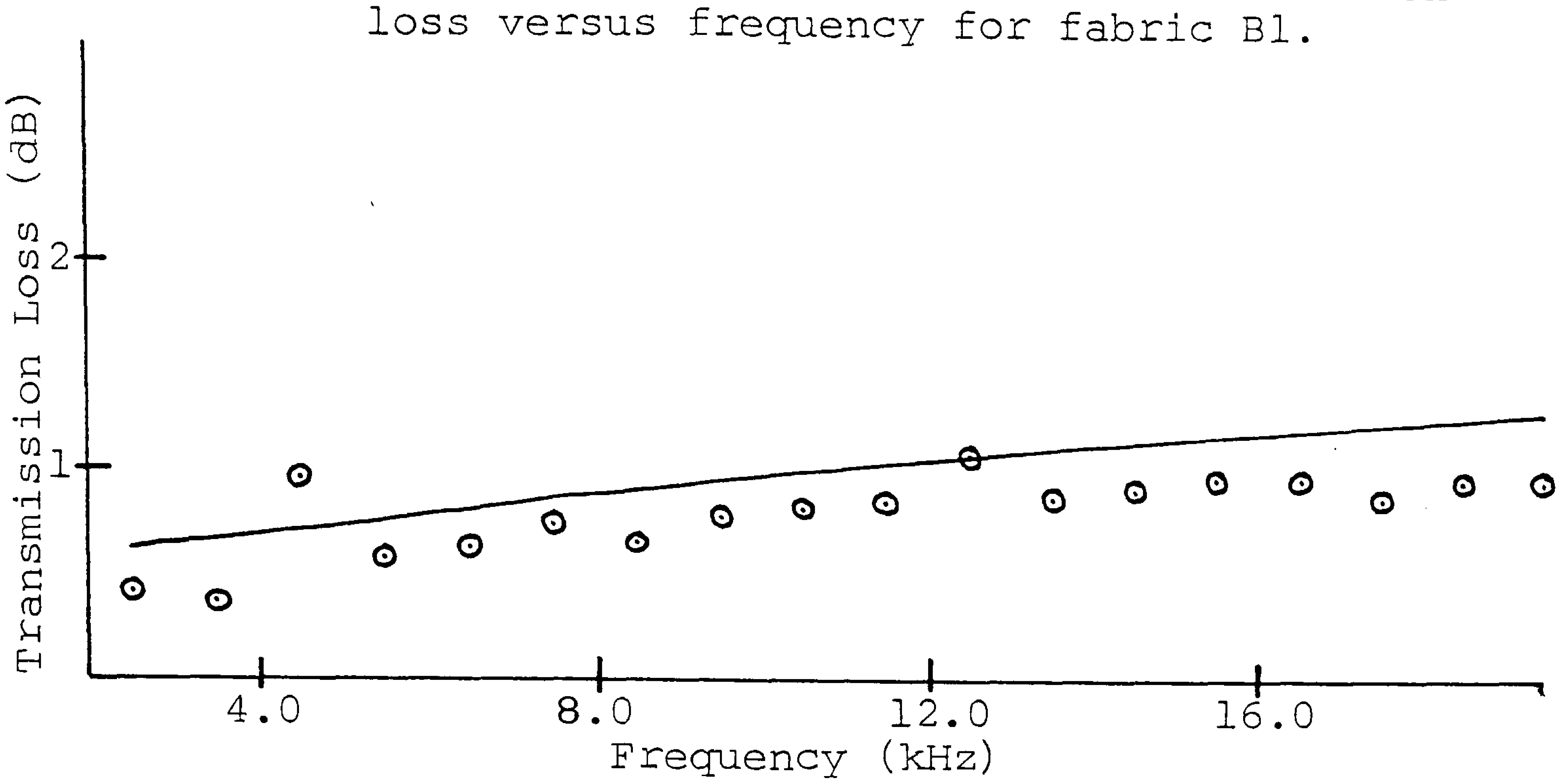


Figure A2.13 Experimental and theoretical transmission loss versus frequency for fabric B2.

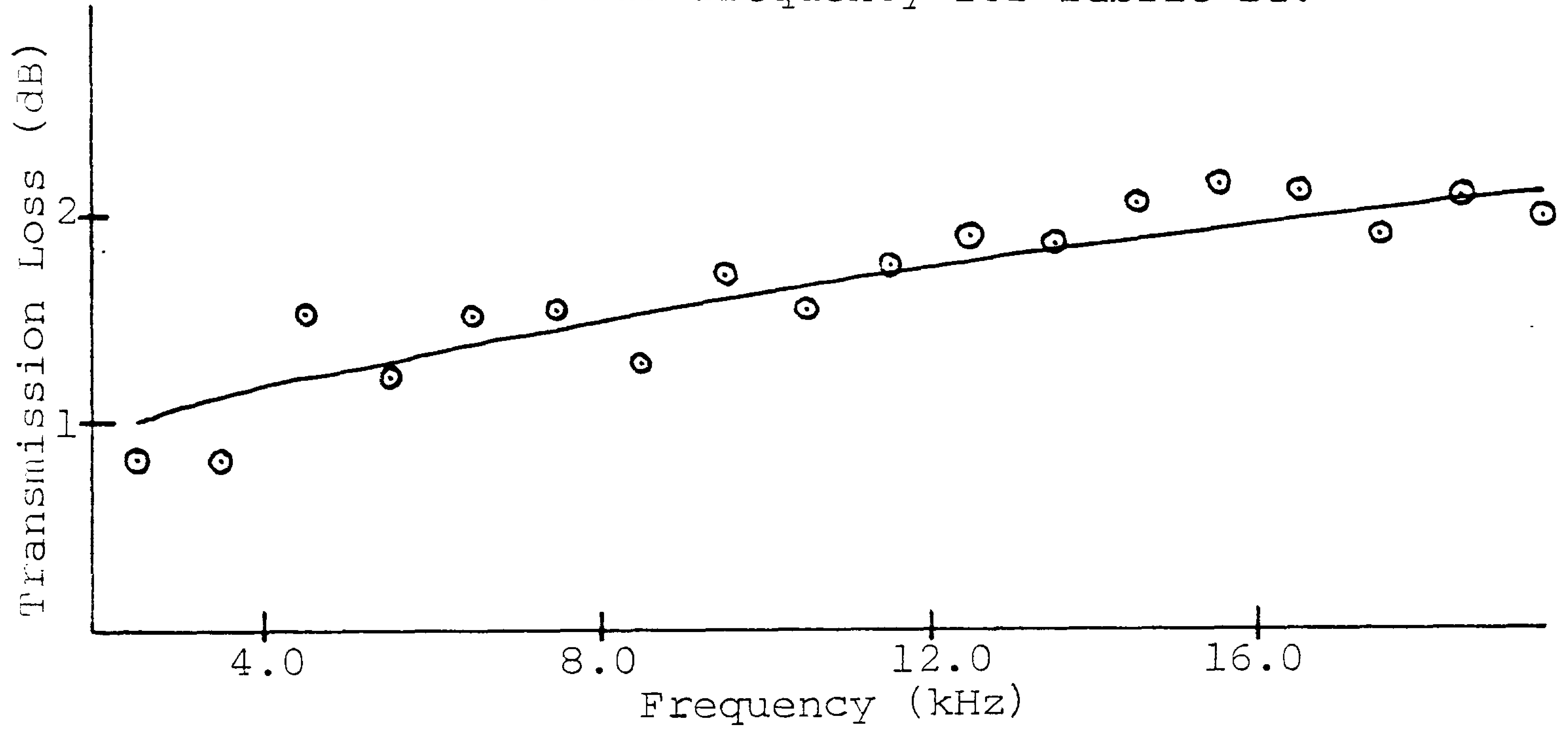


Figure A2.14 Experimental and theoretical transmission loss versus frequency for fabric B3.

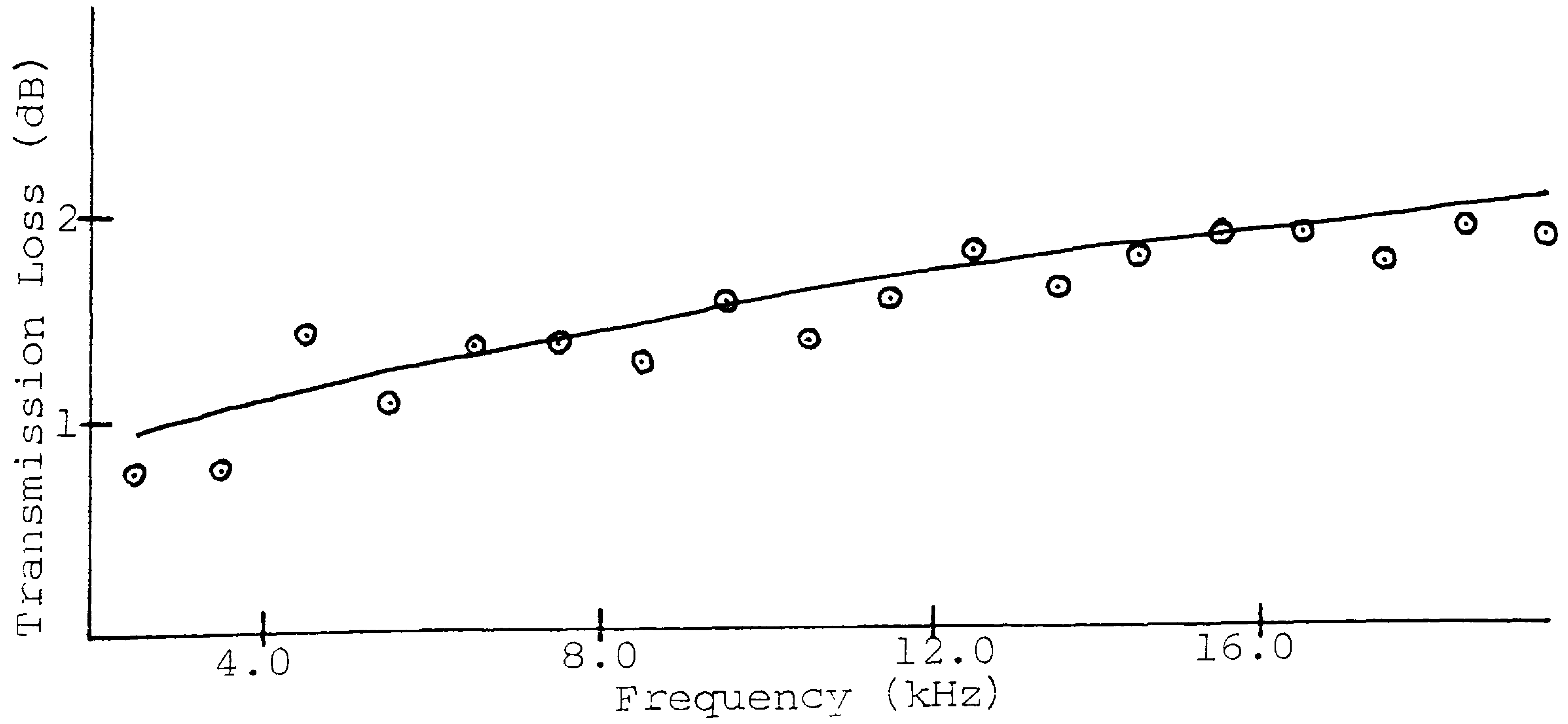


Figure A2.15 Experimental and theoretical transmission loss versus frequency for fabric B4.

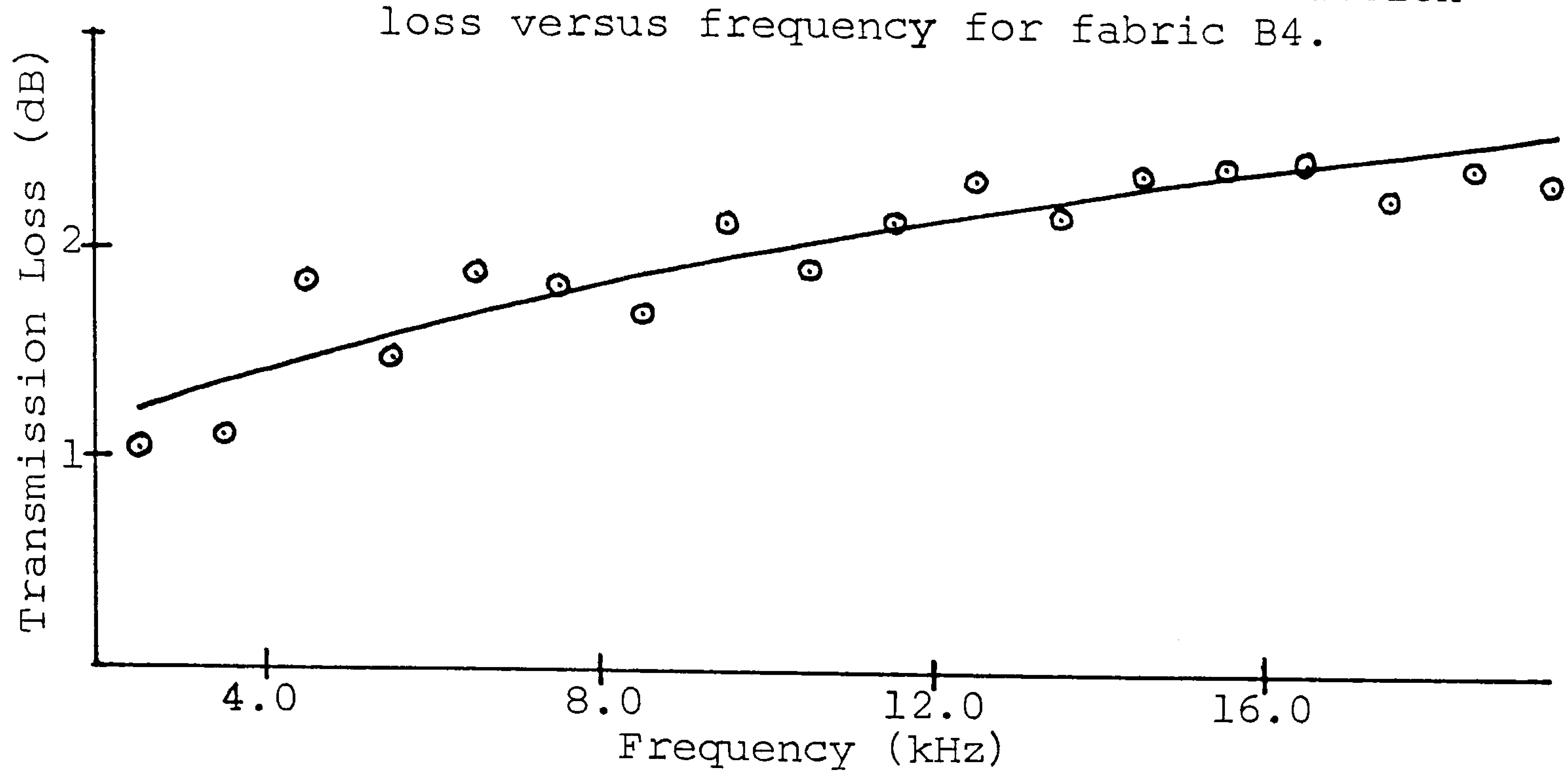


Figure A2.16 Experimental and theoretical transmission loss versus frequency for fabric B5.

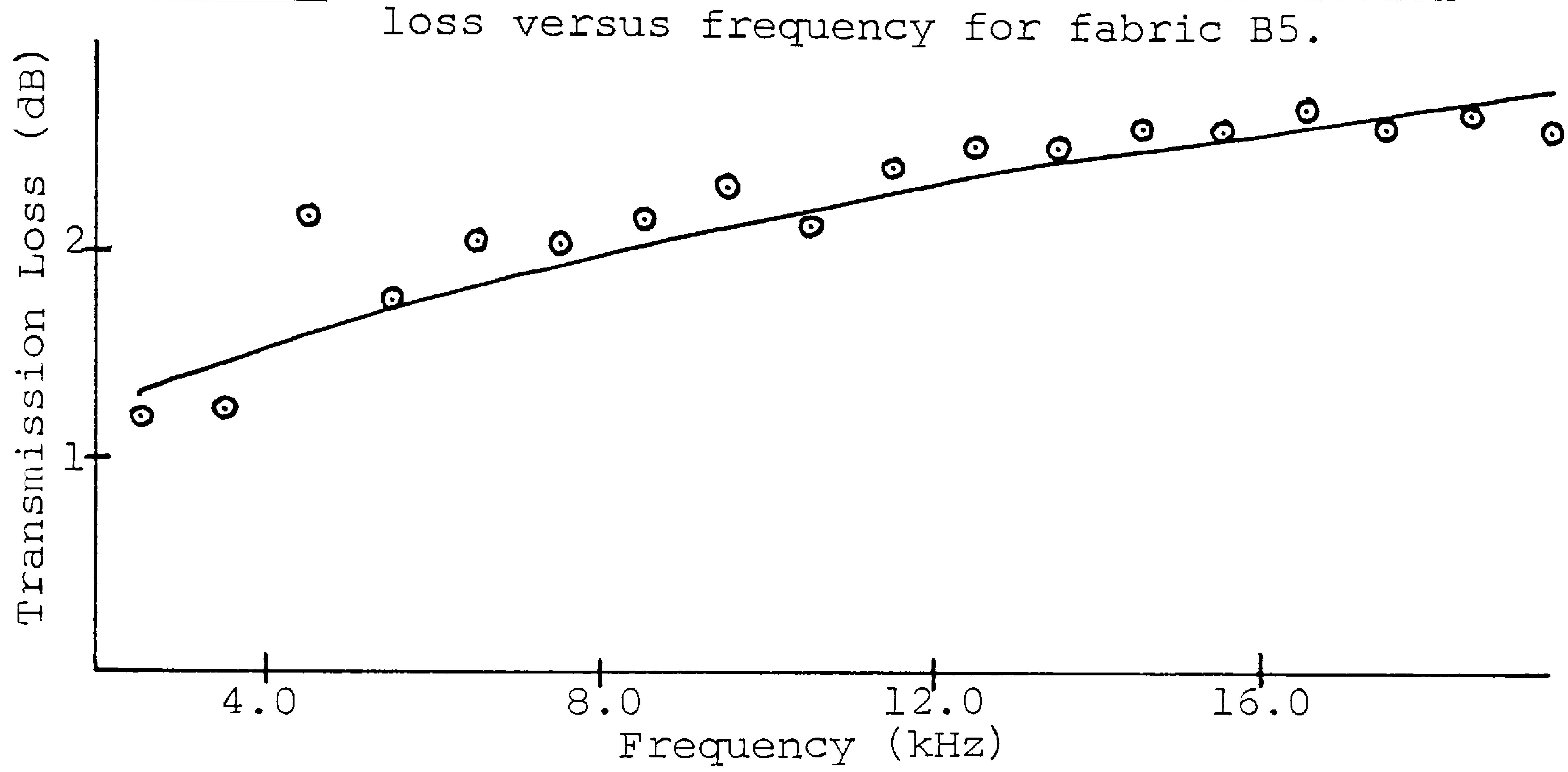


Figure A2.17 Experimental and theoretical transmission loss versus frequency for fabric B6.

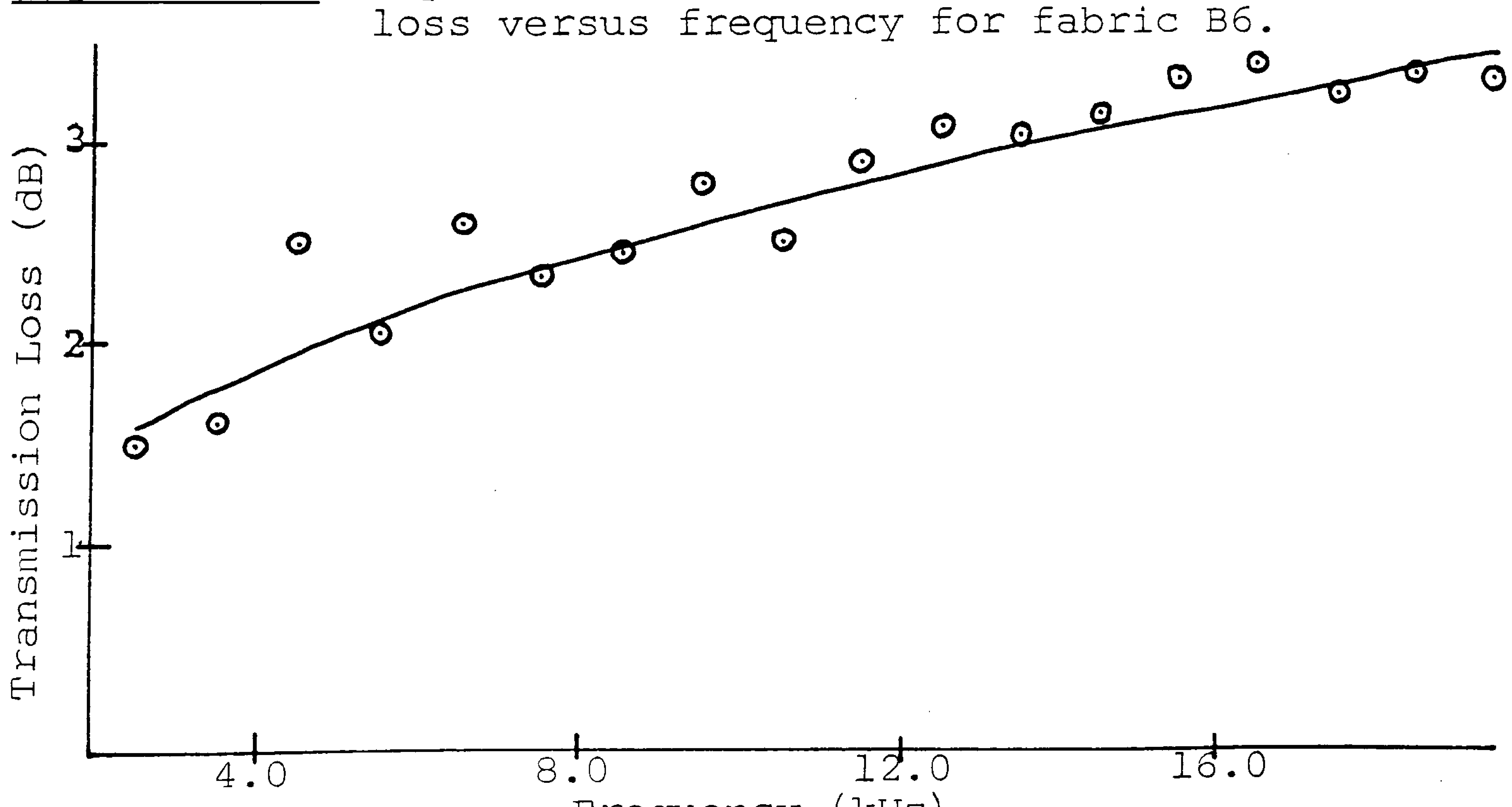


Figure A2.18 Experimental and theoretical transmission loss versus frequency for fabric B7.

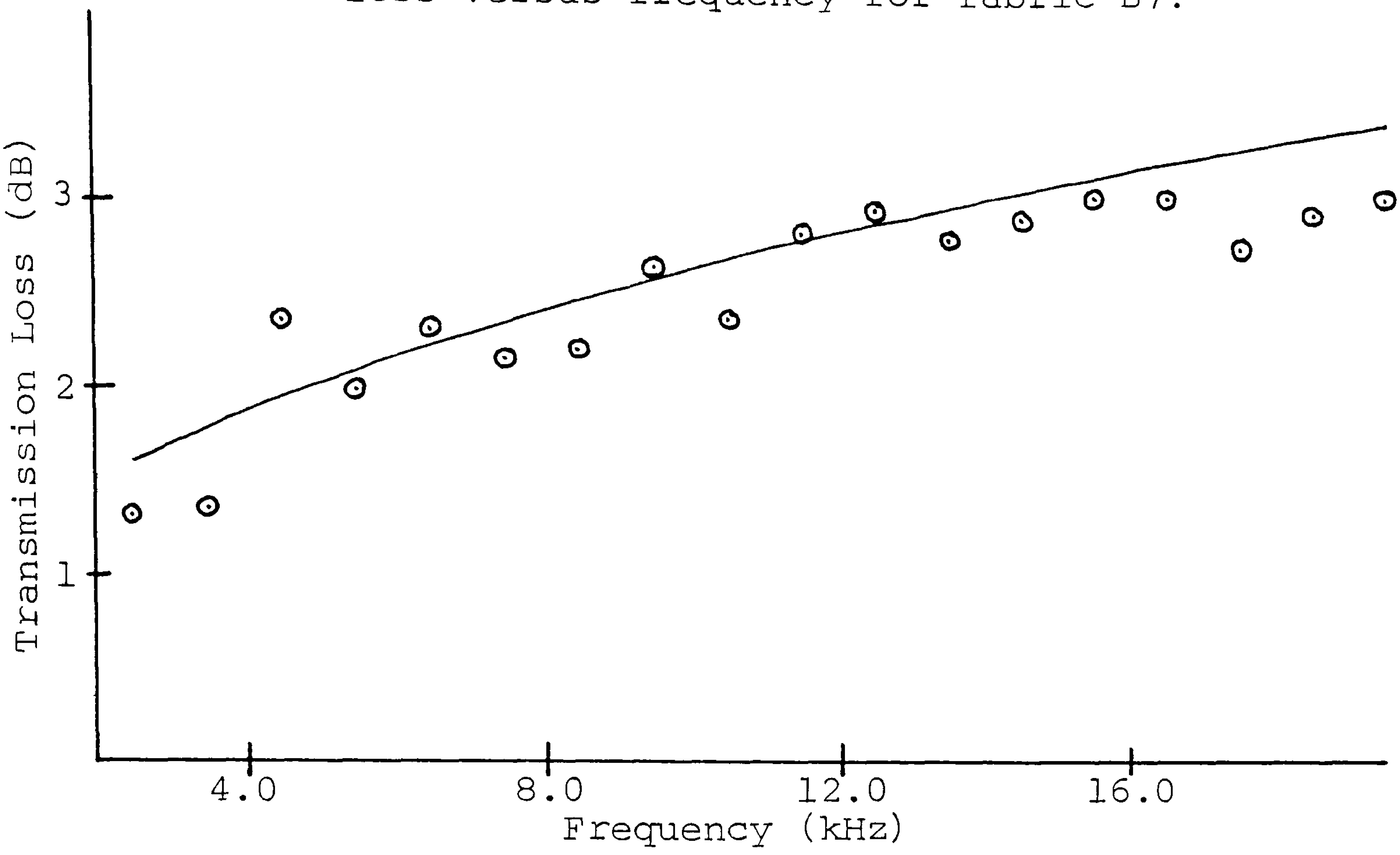


Figure A2.19 Experimental and theoretical transmission loss versus frequency for fabric B8.

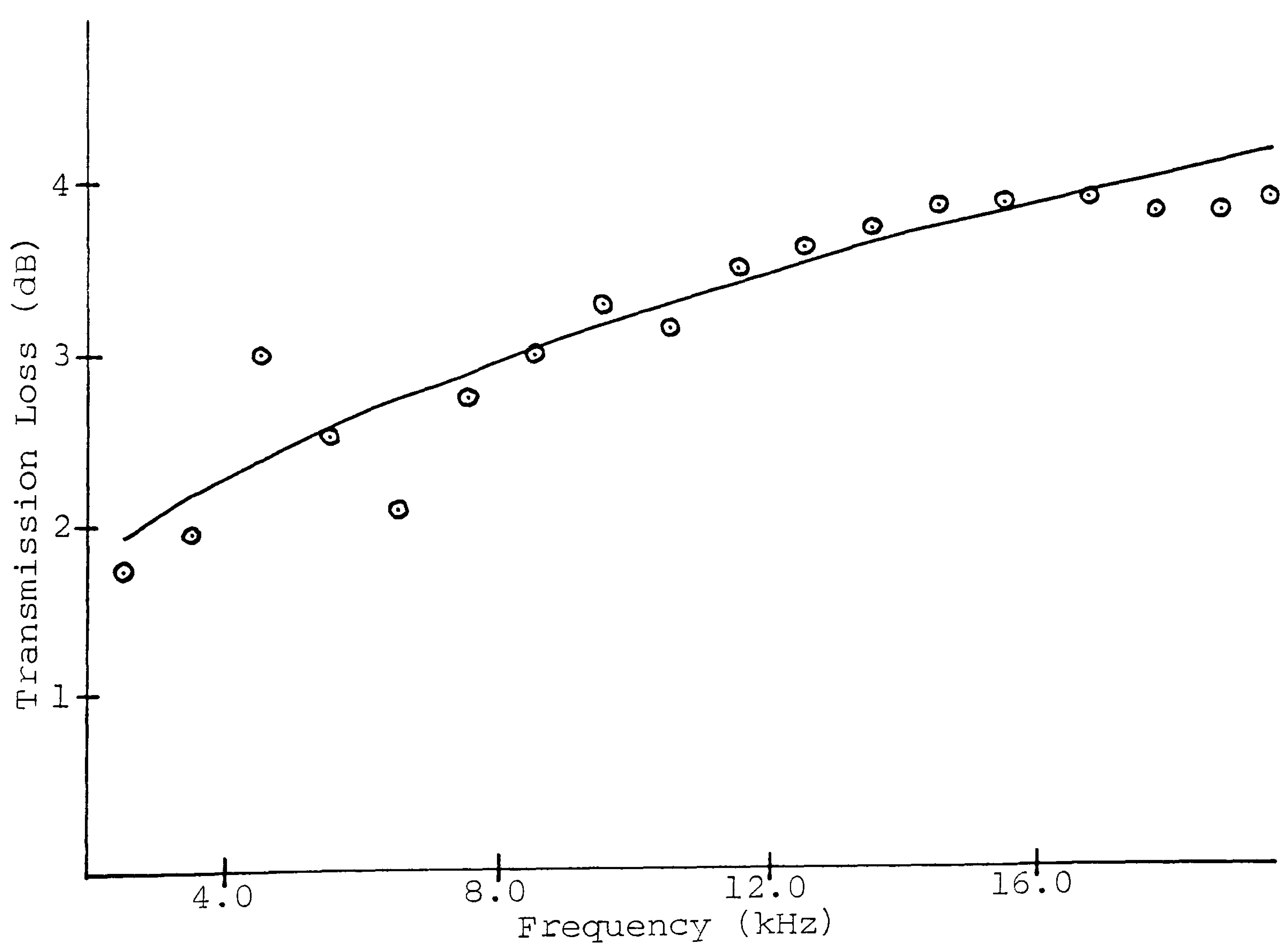


Figure A2.20 Experimental and theoretical transmission loss versus frequency for fabric C1.

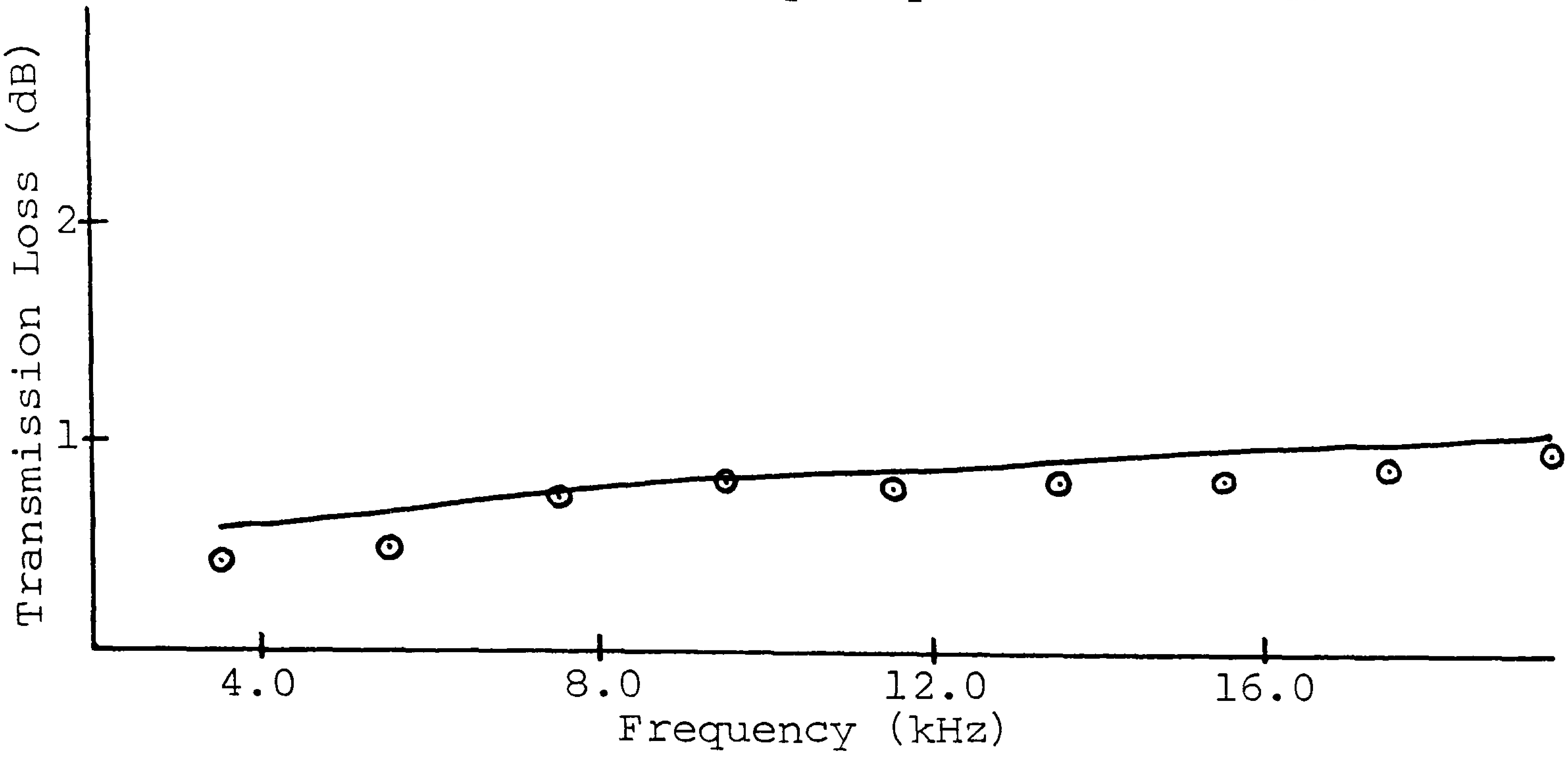


Figure A2. 21 Experimental and theoretical transmission loss versus frequency for fabric C2.

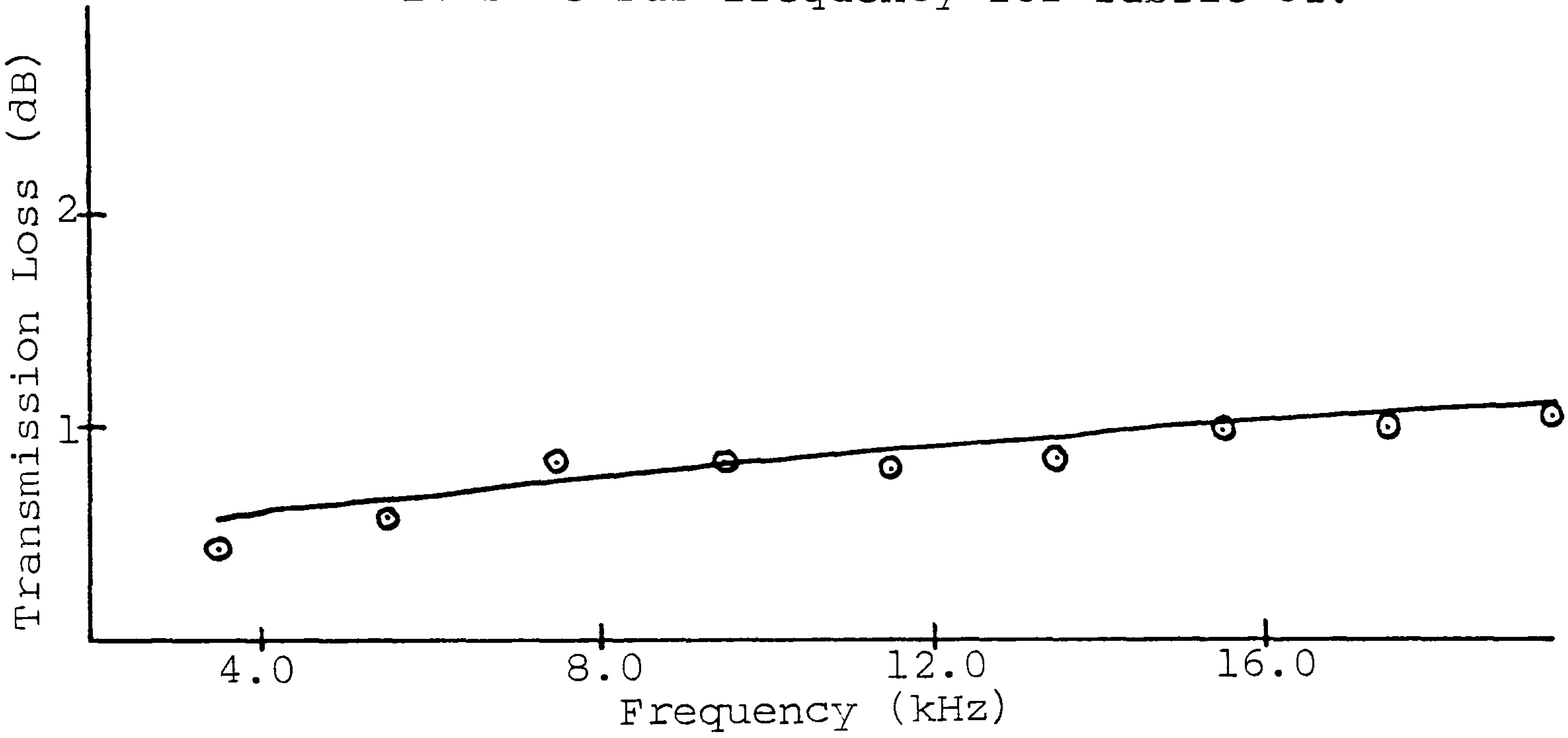


Figure A2.22 Experimental and theoretical transmission loss versus frequency for fabric C3.

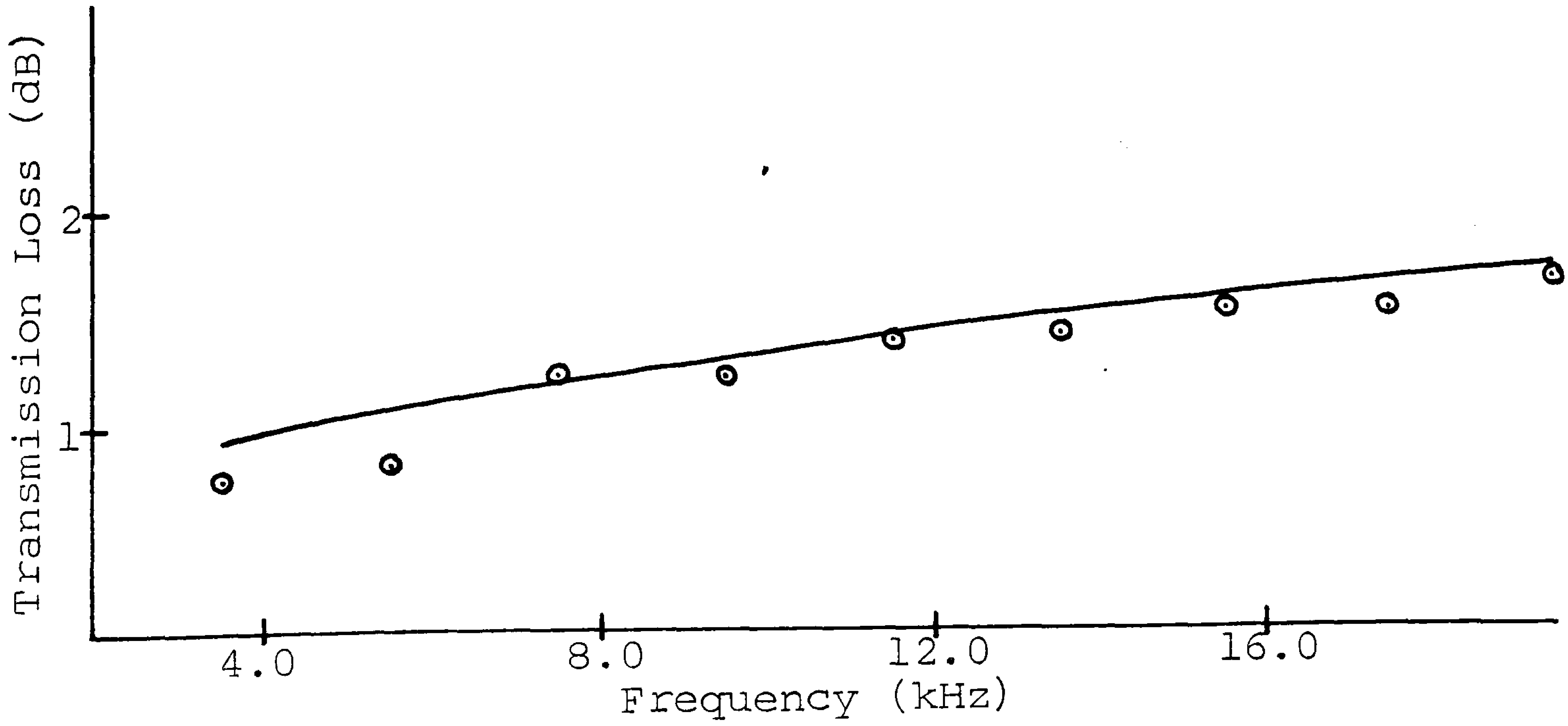


Figure A2. 23 Experimental and theoretical transmission loss versus frequency for fabric C4.

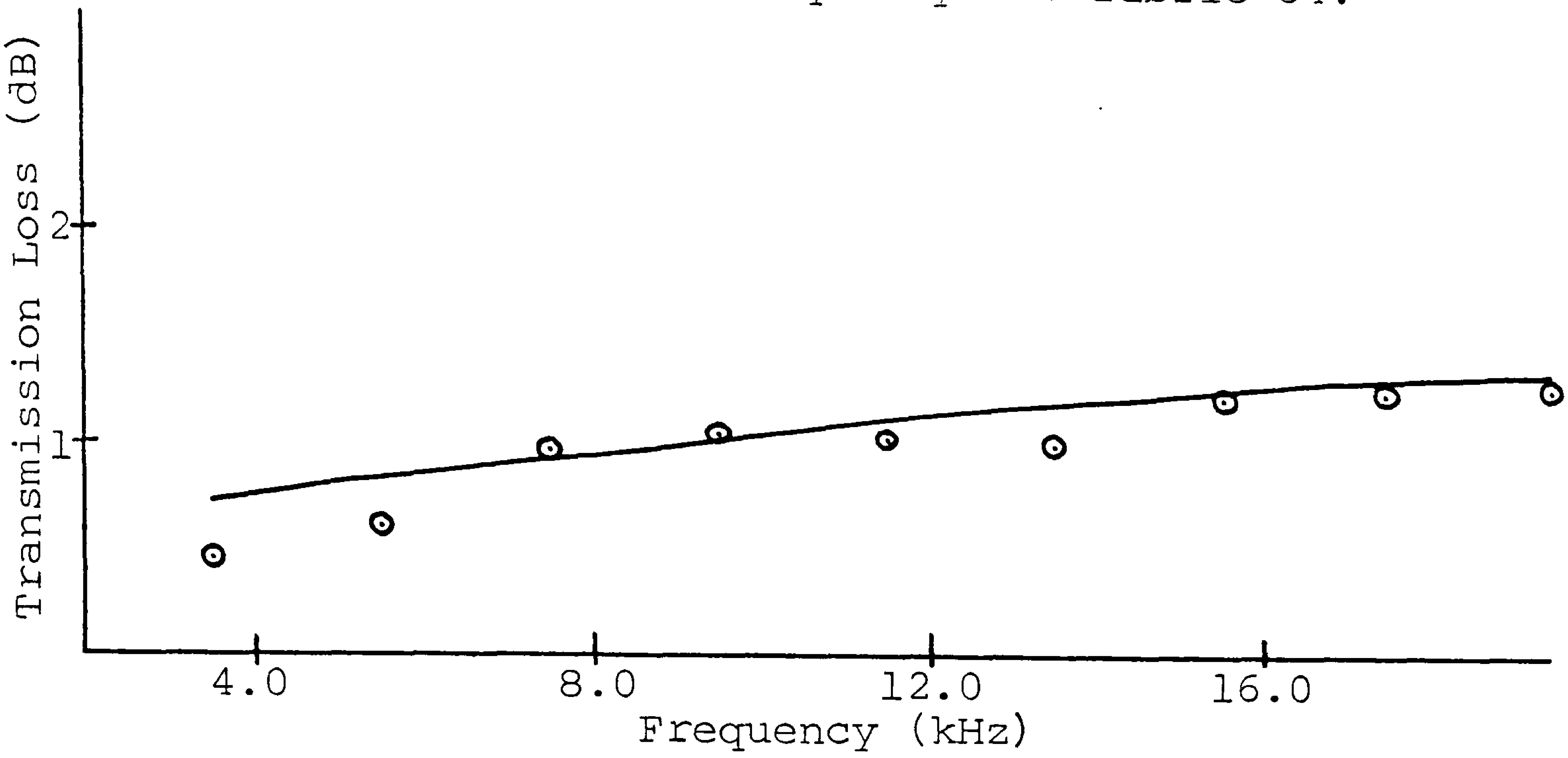


Figure A2.24 Experimental and theoretical transmission loss versus frequency for fabric C5.

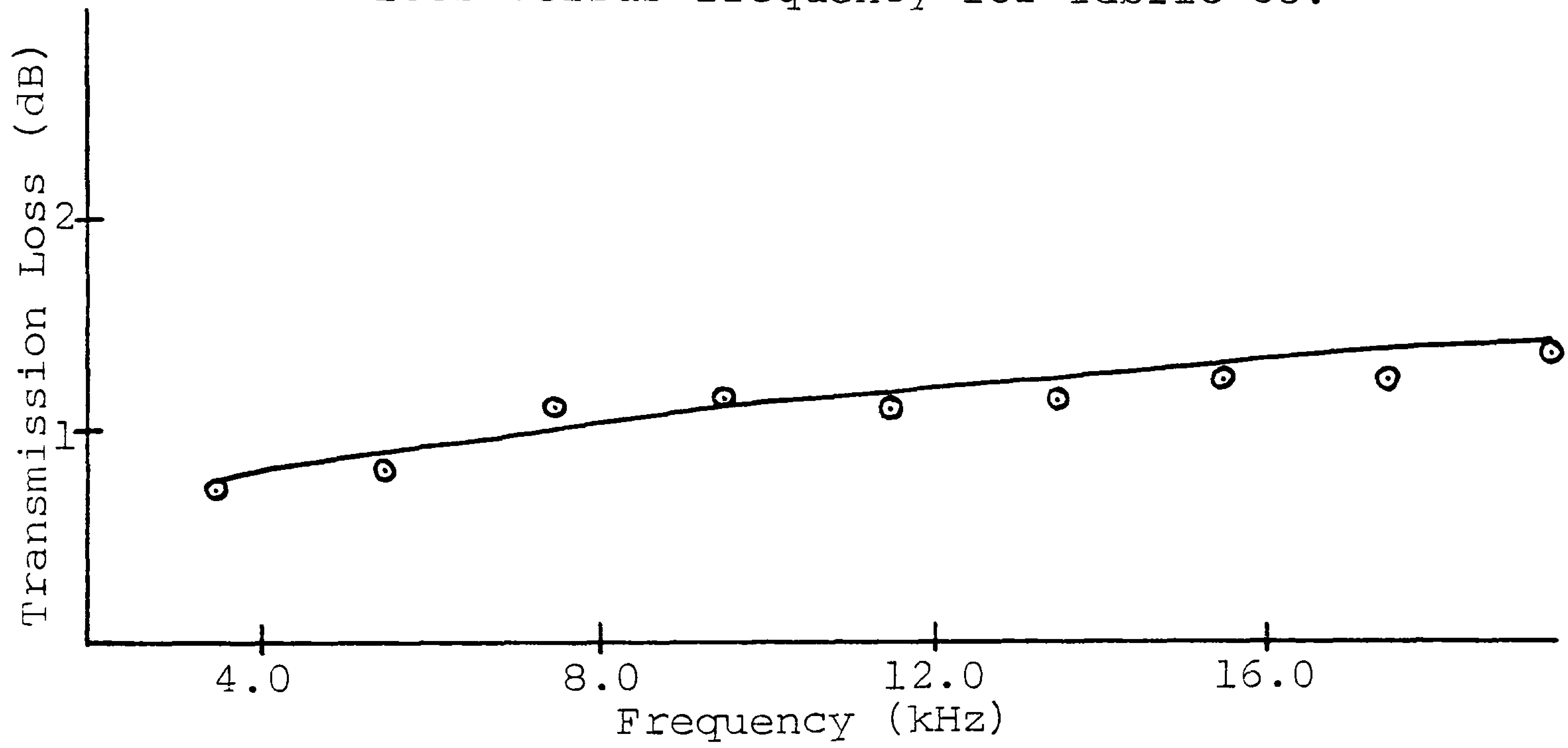


Figure A2.25 Experimental and theoretical transmission loss versus frequency for fabric C6.

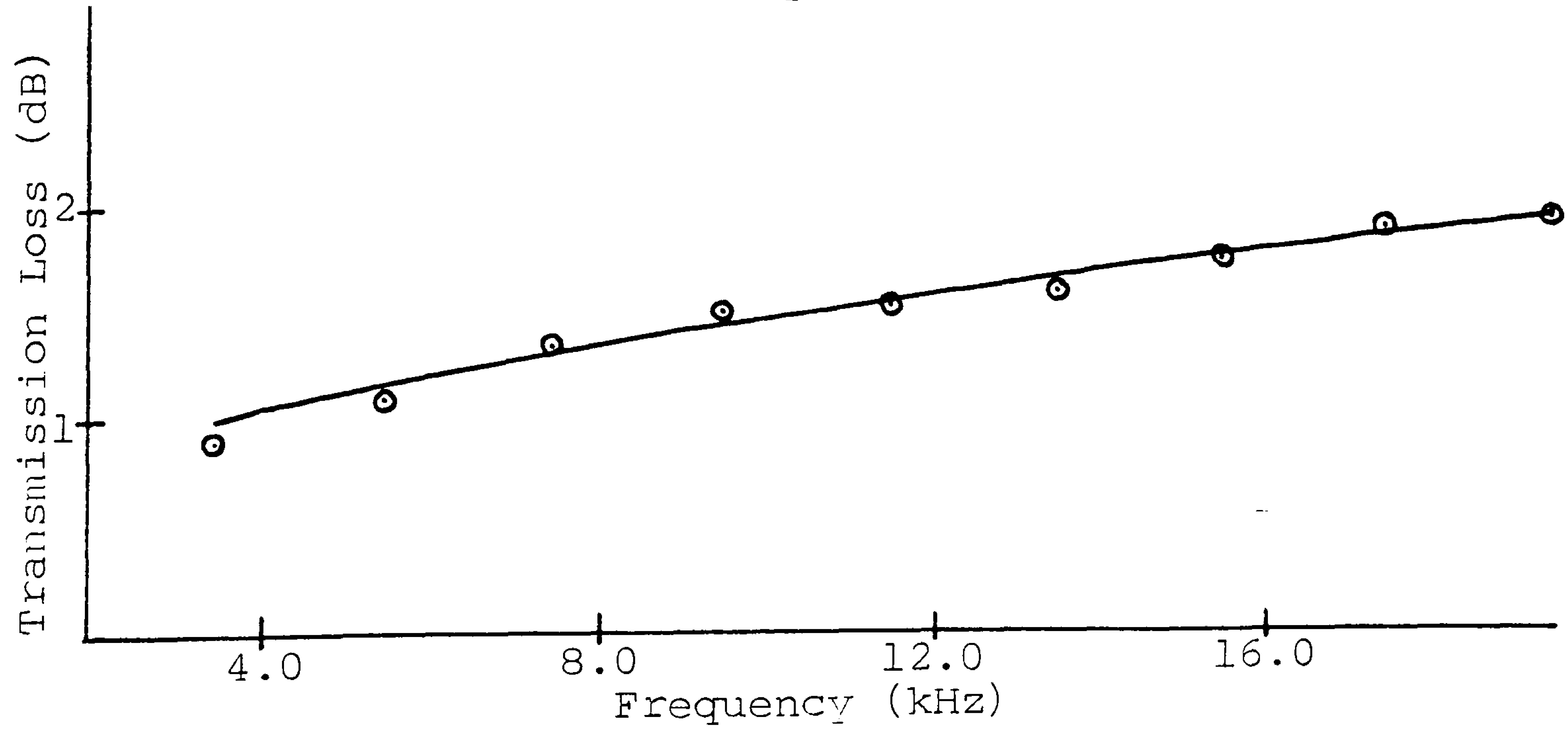


Figure A2.26 Experimental and theoretical transmission loss versus frequency for fabric C7.

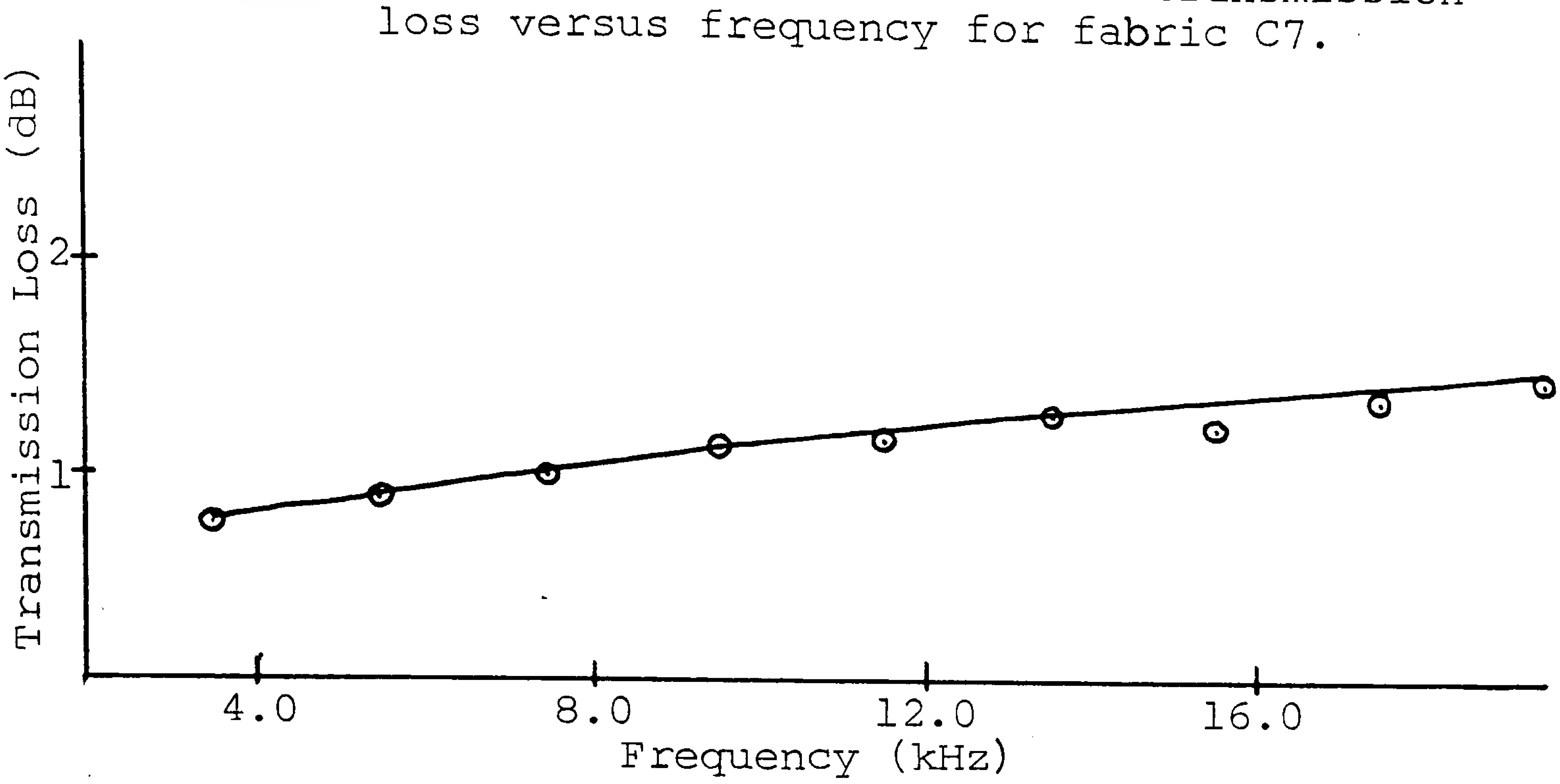


Figure A2.27 Experimental and theoretical transmission loss versus frequency for fabric C8.

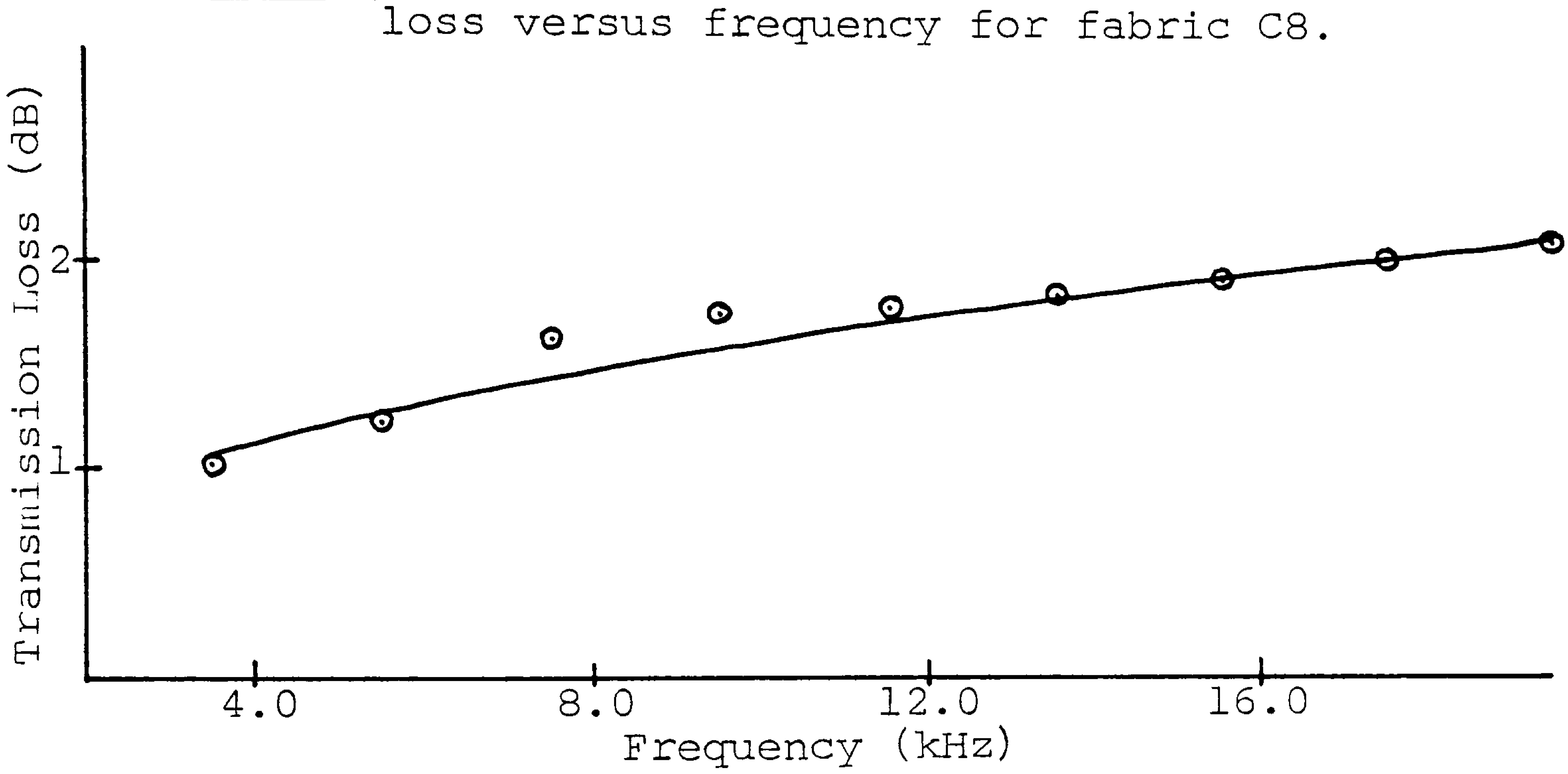


Figure A2.28 Experimental and theoretical transmission loss versus frequency for fabric C9

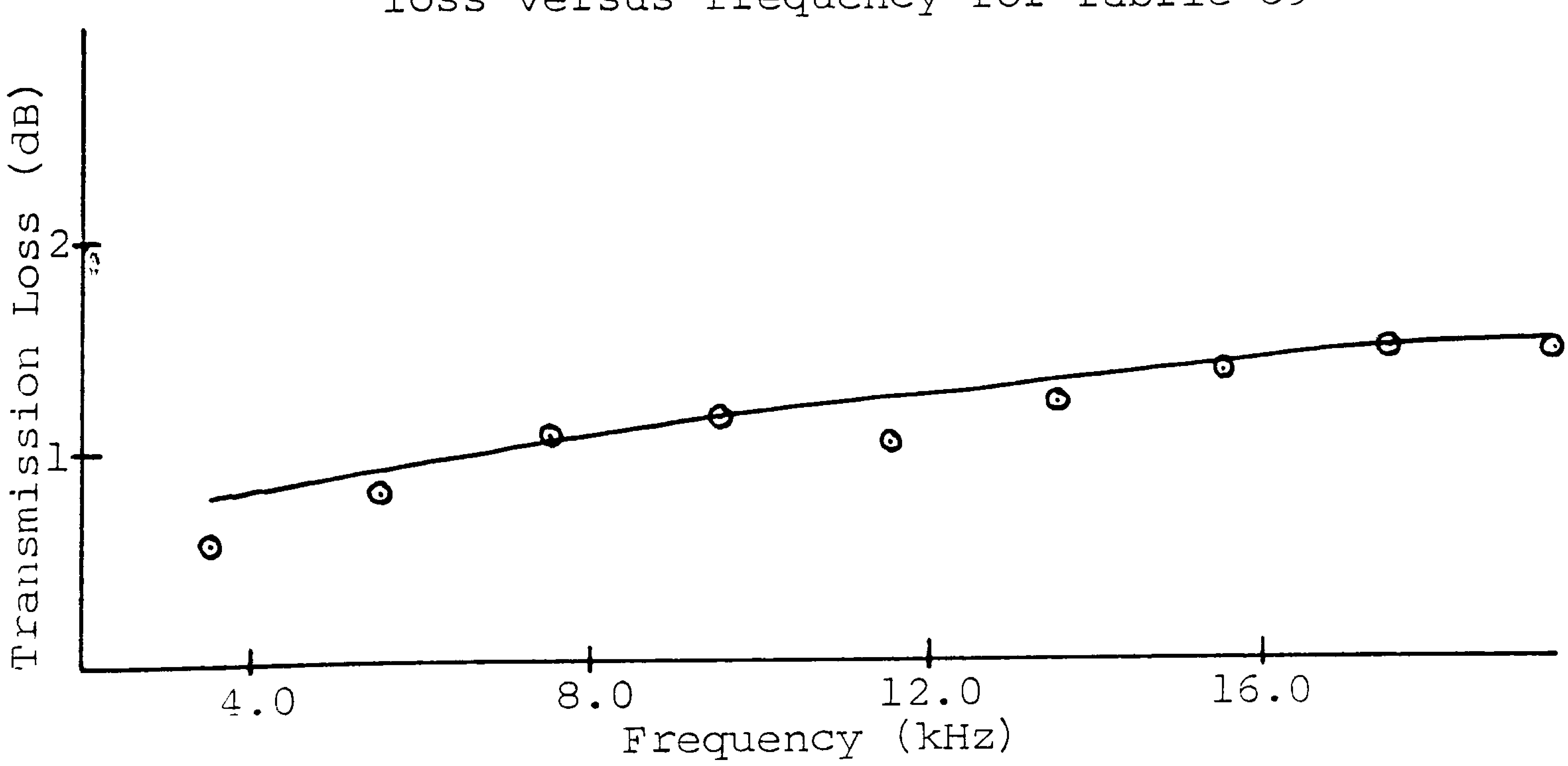


Figure A2.29 Experimental and theoretical transmission loss versus frequency for fabric C10.

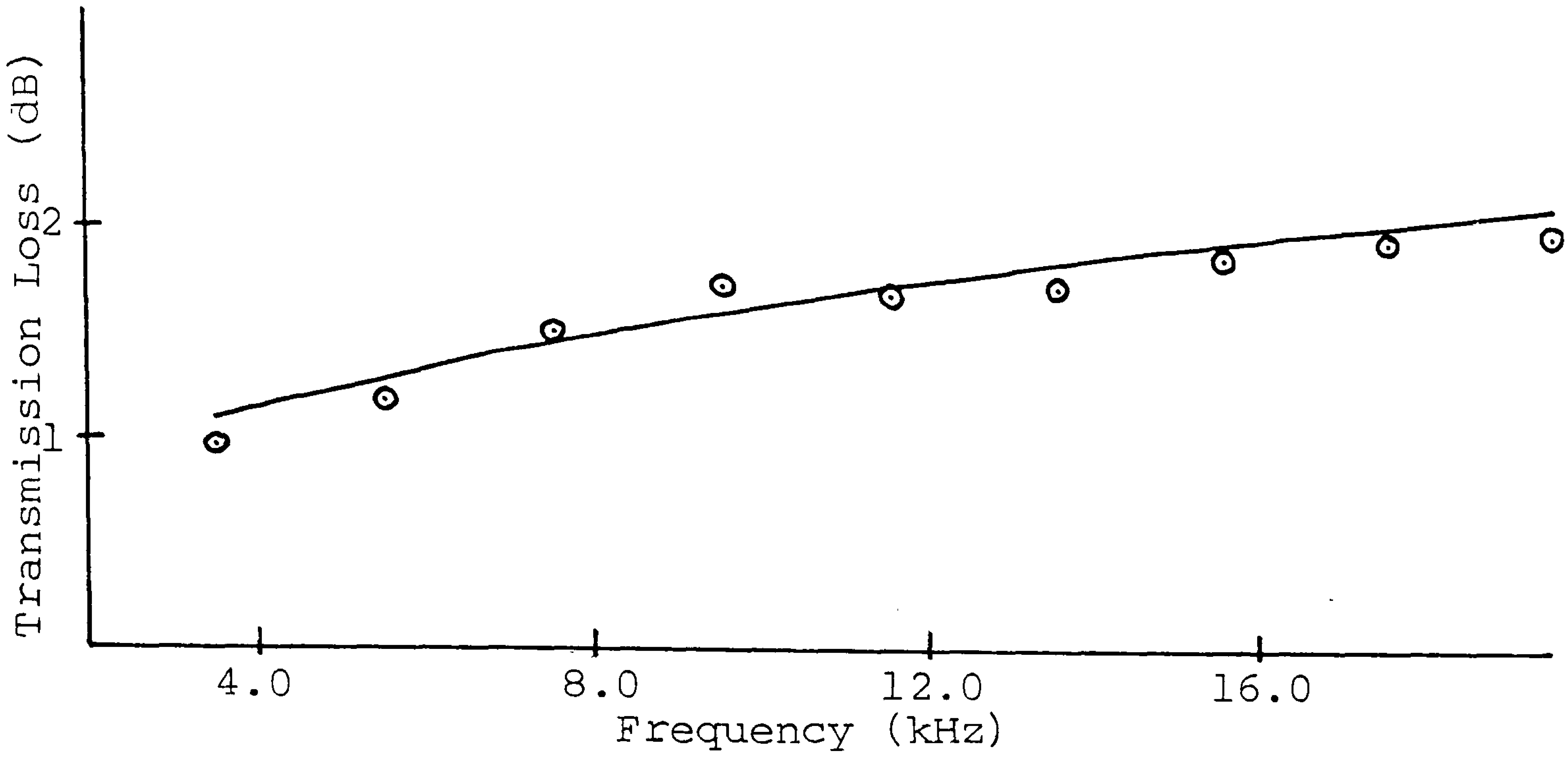


Figure A2.30 Experimental and theoretical transmission loss versus frequency for fabric C11.

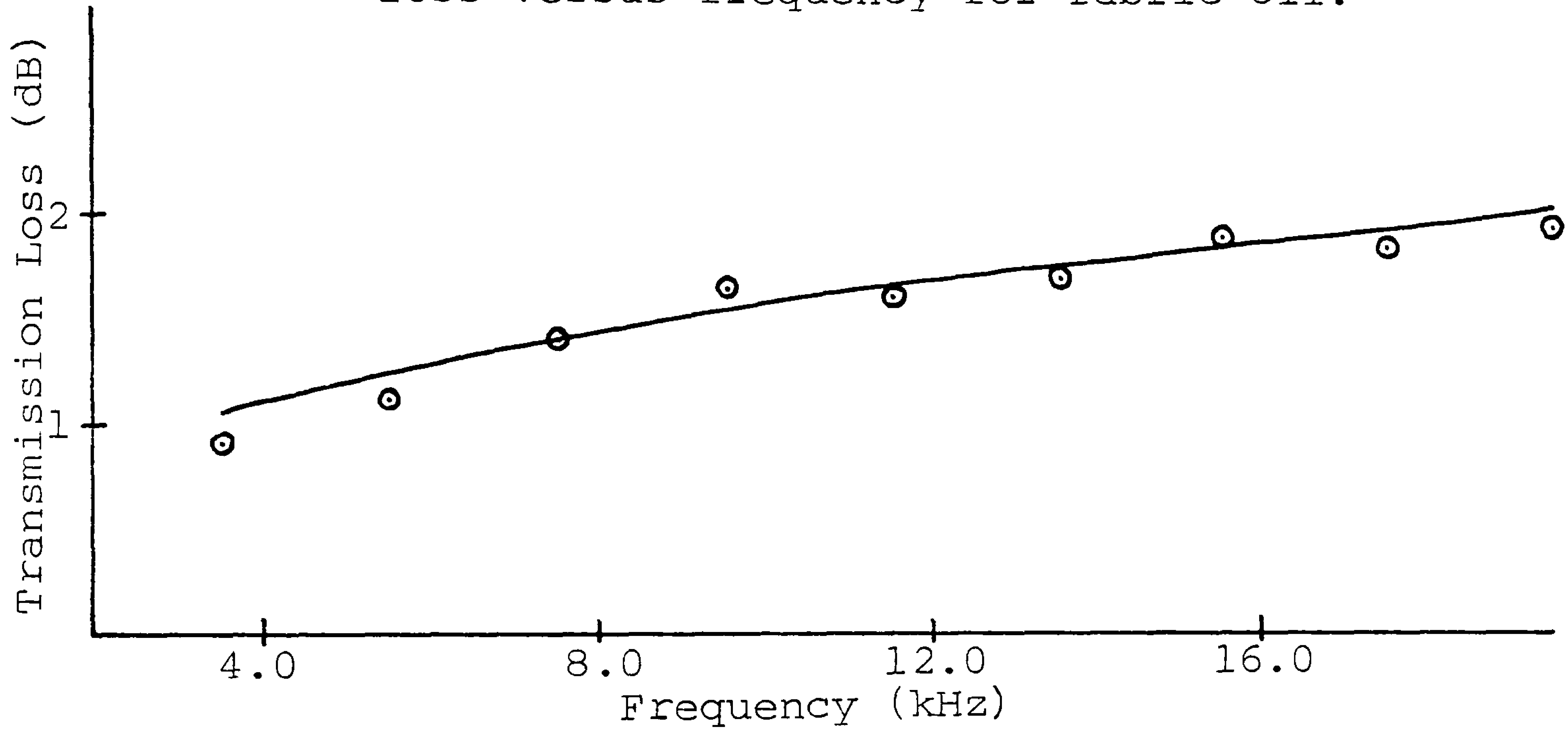


Figure A2.31 Experimental and theoretical transmission loss versus frequency for fabric C12.

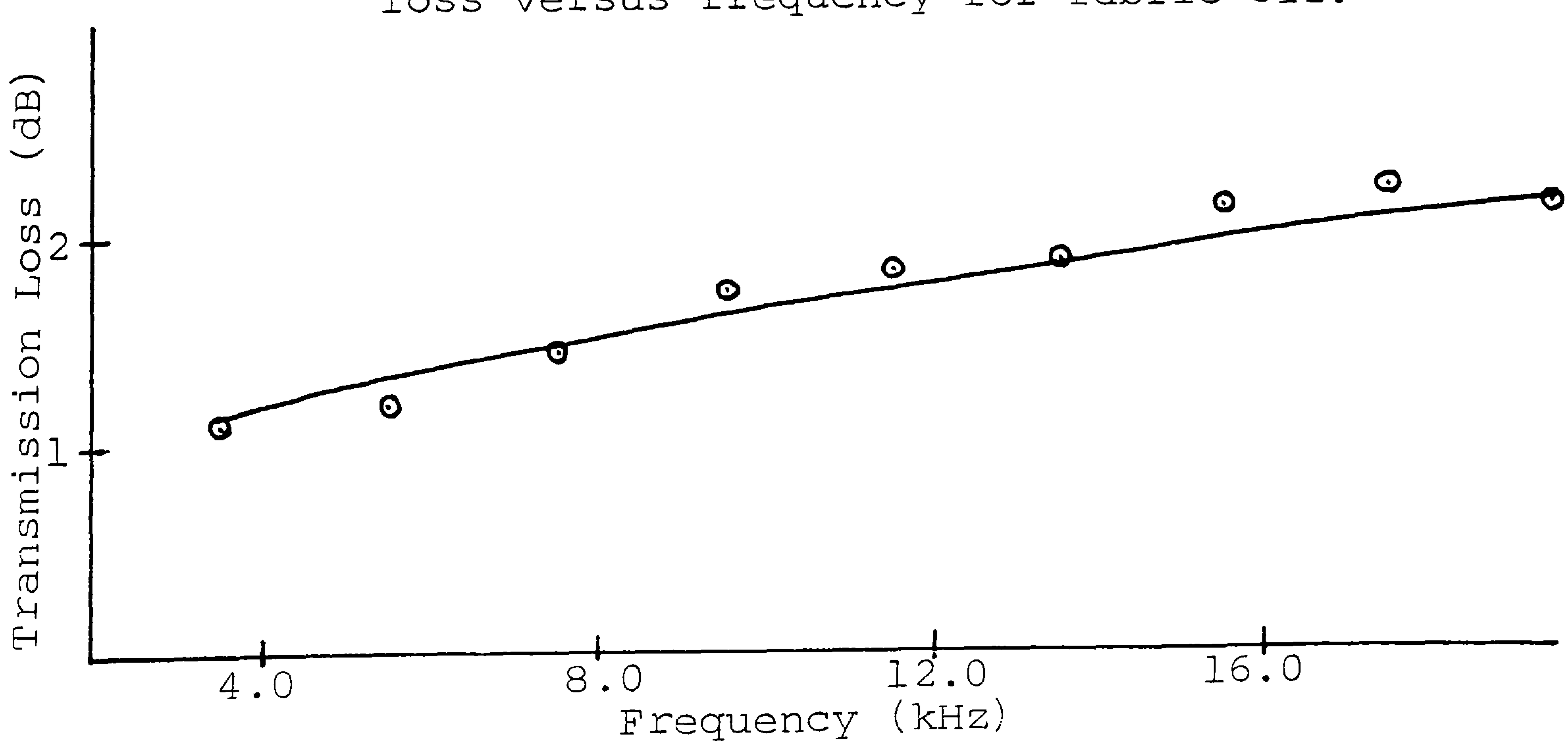


Figure A2.32 Experimental and theoretical transmission loss versus frequency for fabric C13.

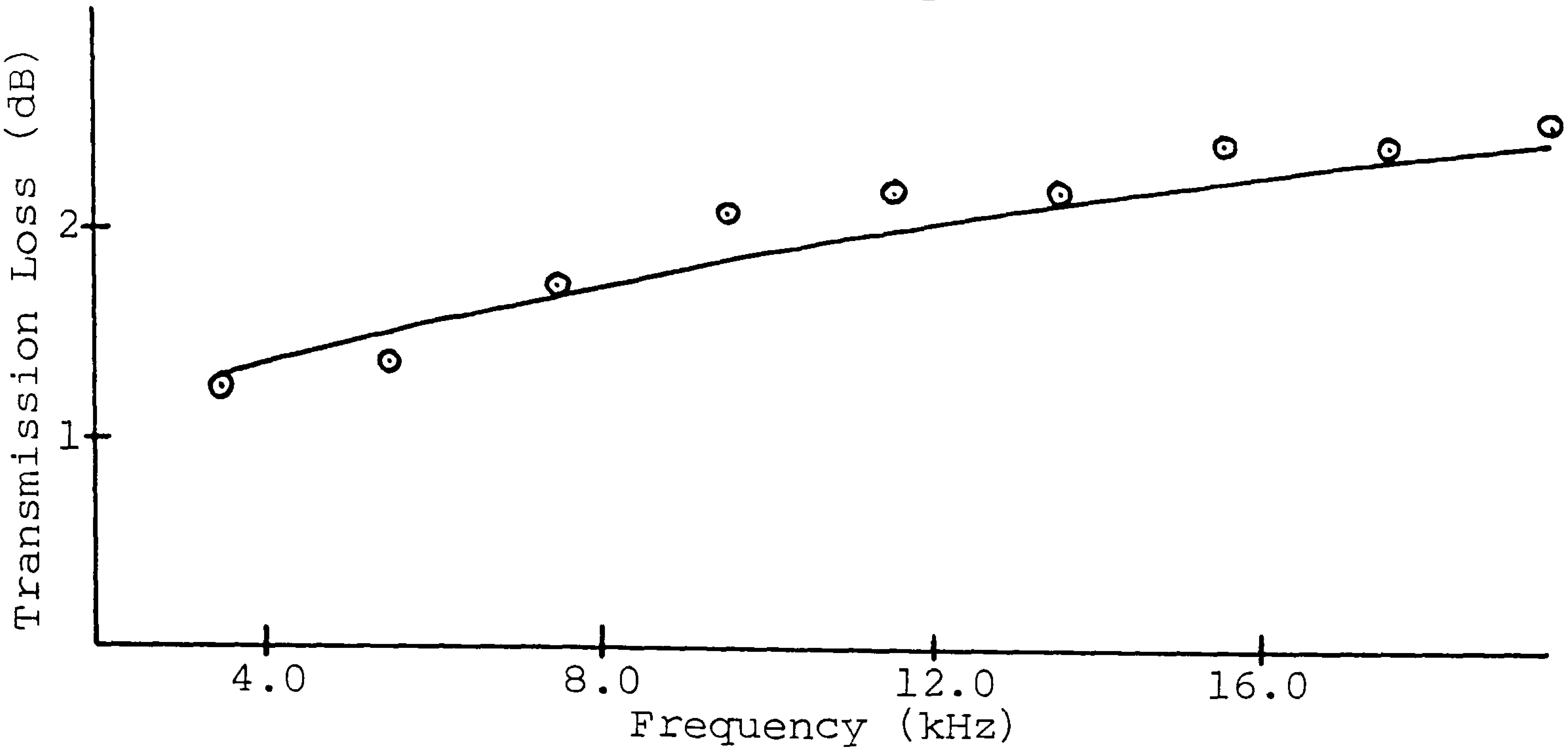


Figure A2.33 Experimental and theoretical transmission loss versus frequency for fabric C14.

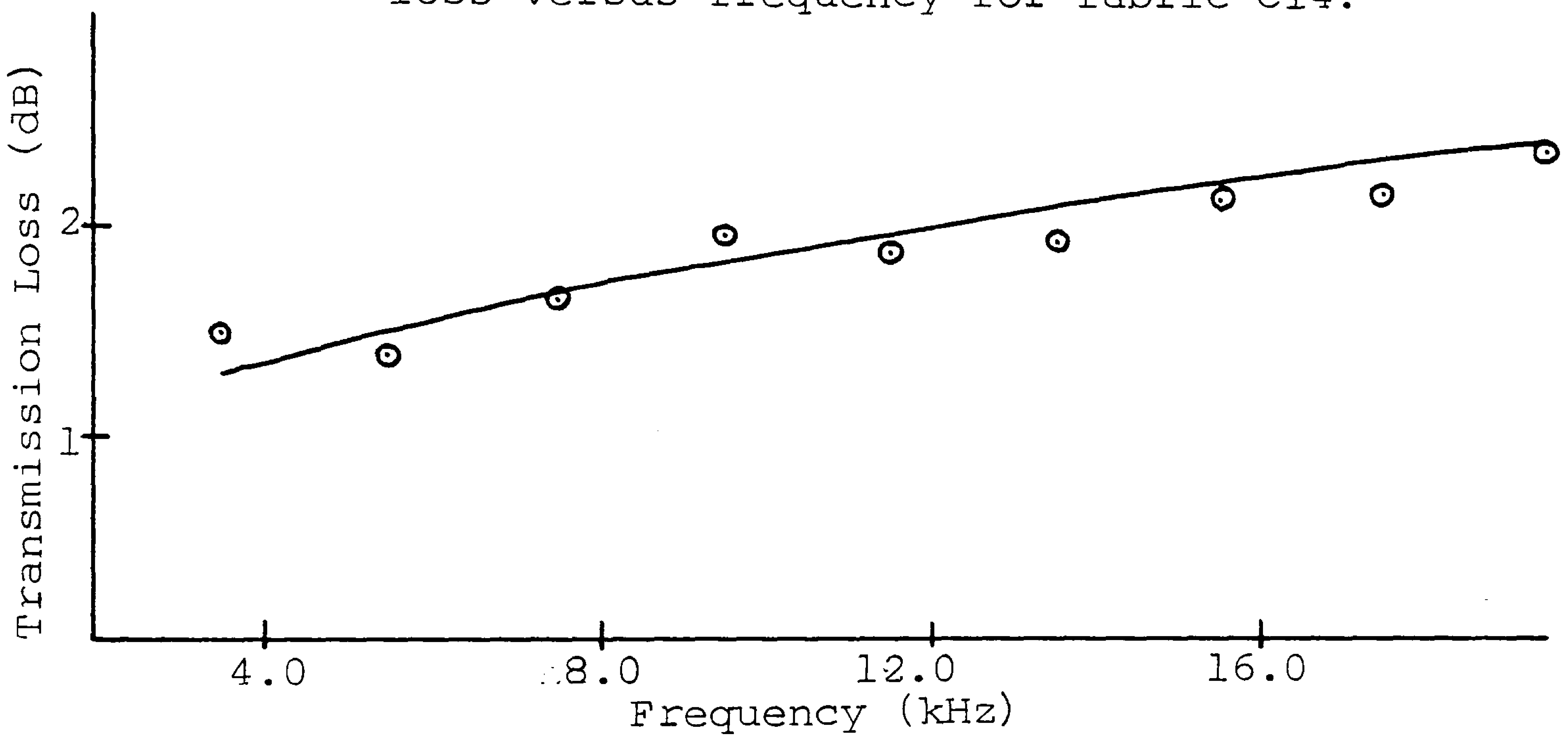


Figure A2.34 Experimental and theoretical transmission loss versus frequency for fabric C15.

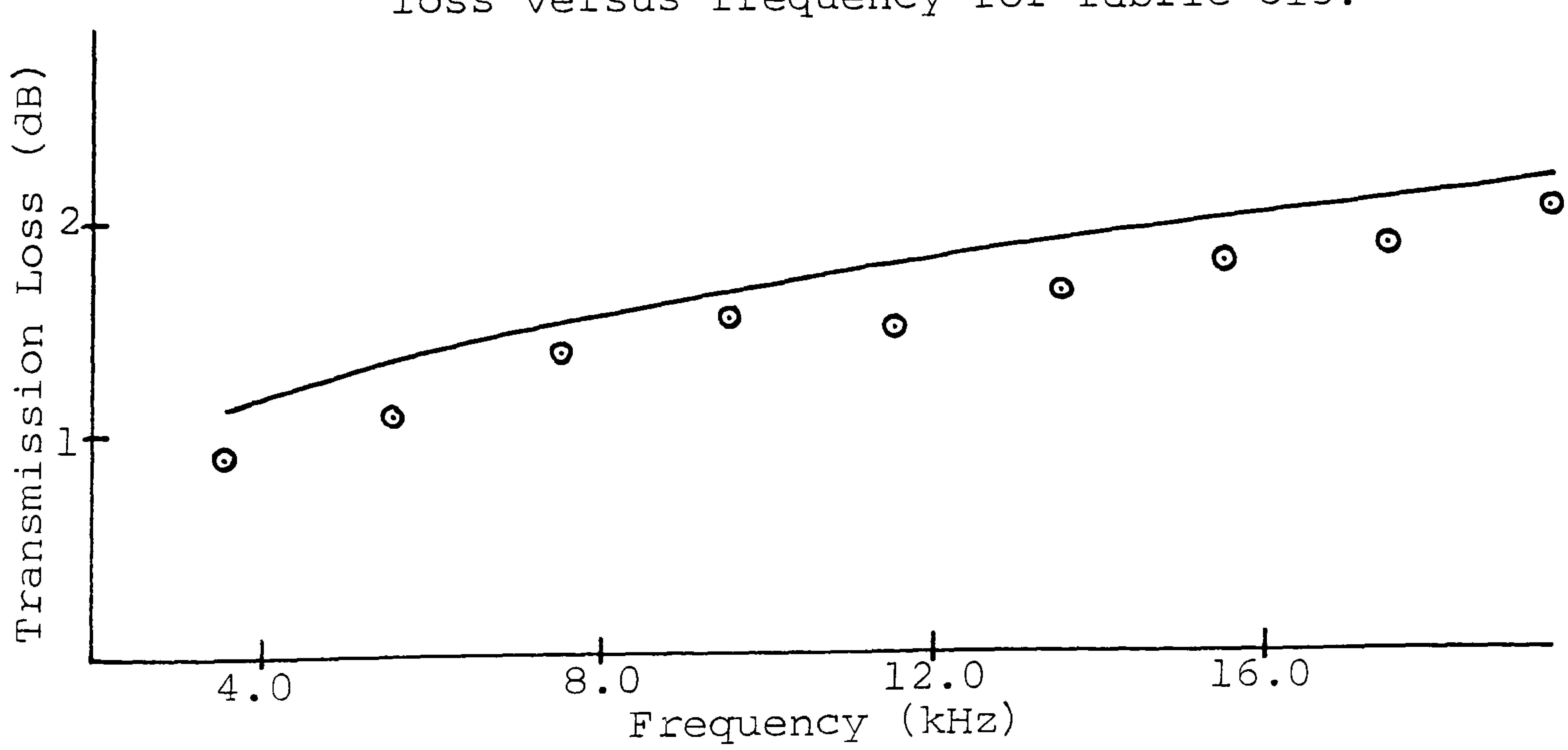


Figure A2.35 Experimental and theoretical transmission loss versus frequency for fabric C16.

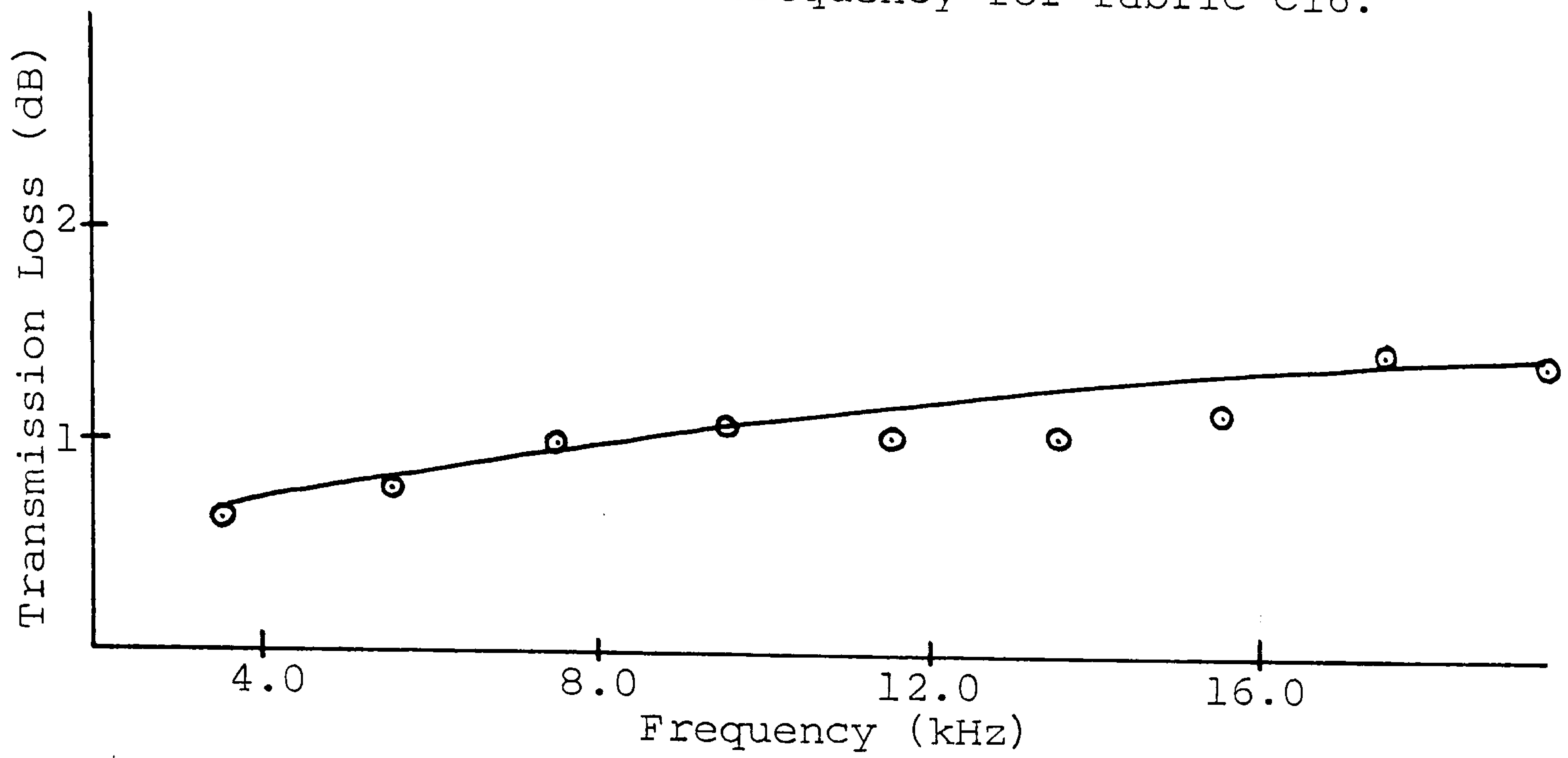


Figure A2.36 Experimental and theoretical transmission loss versus frequency for fabric C17.

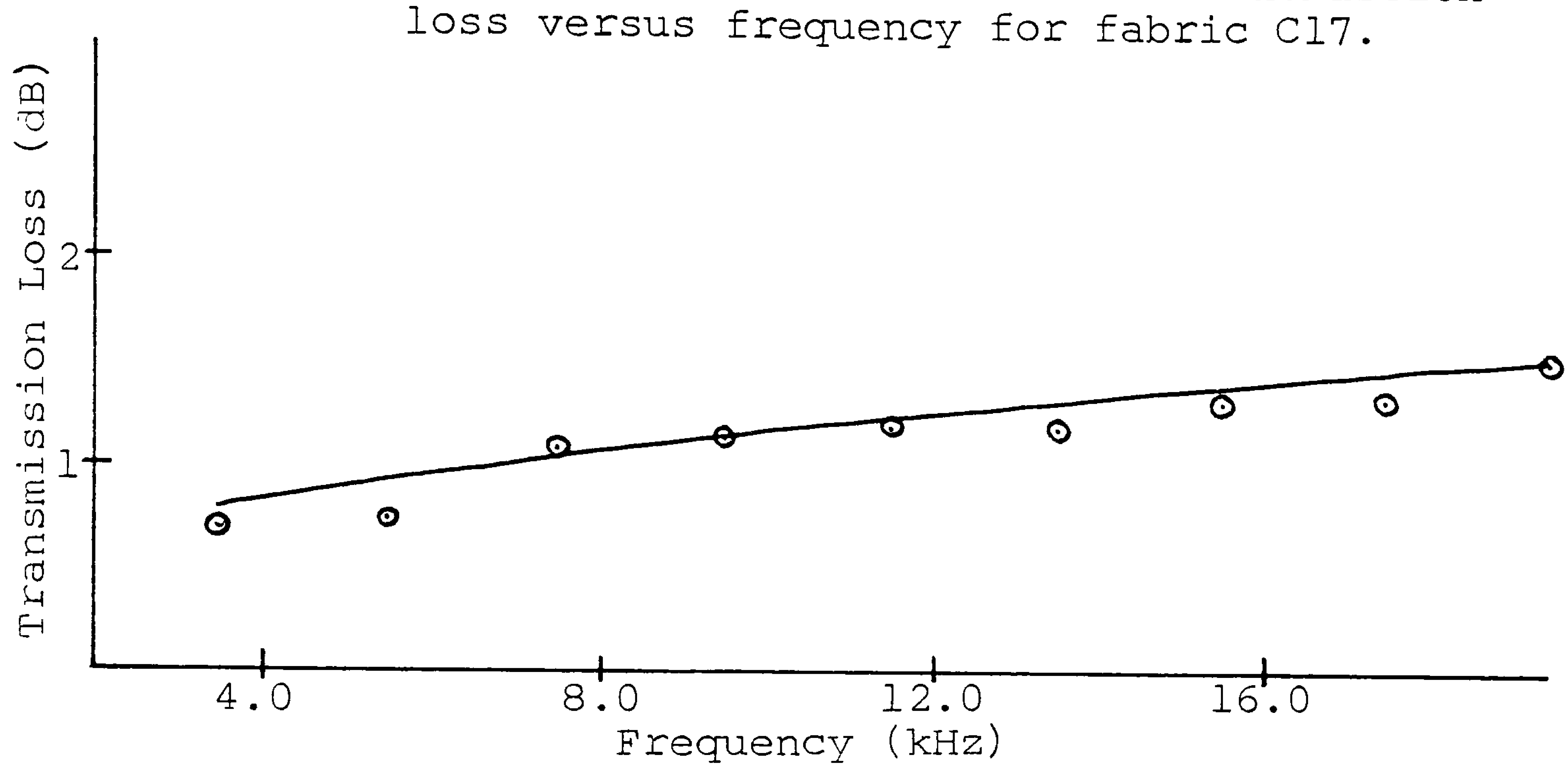


Figure A2.37 Experimental and theoretical transmission loss versus frequency for fabric C18.

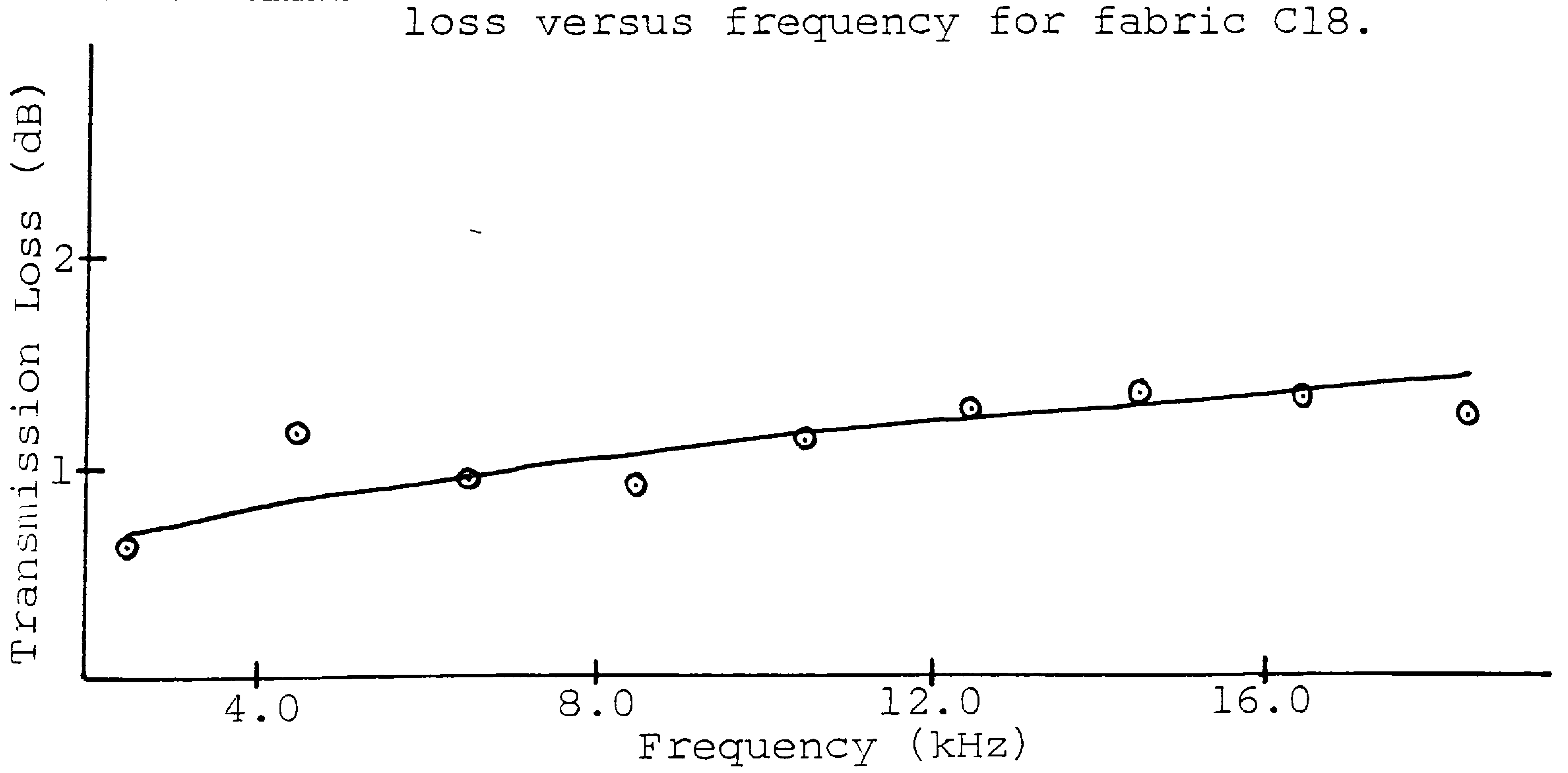


Figure A2.38 Experimental and theoretical transmission loss versus frequency for fabric C19.

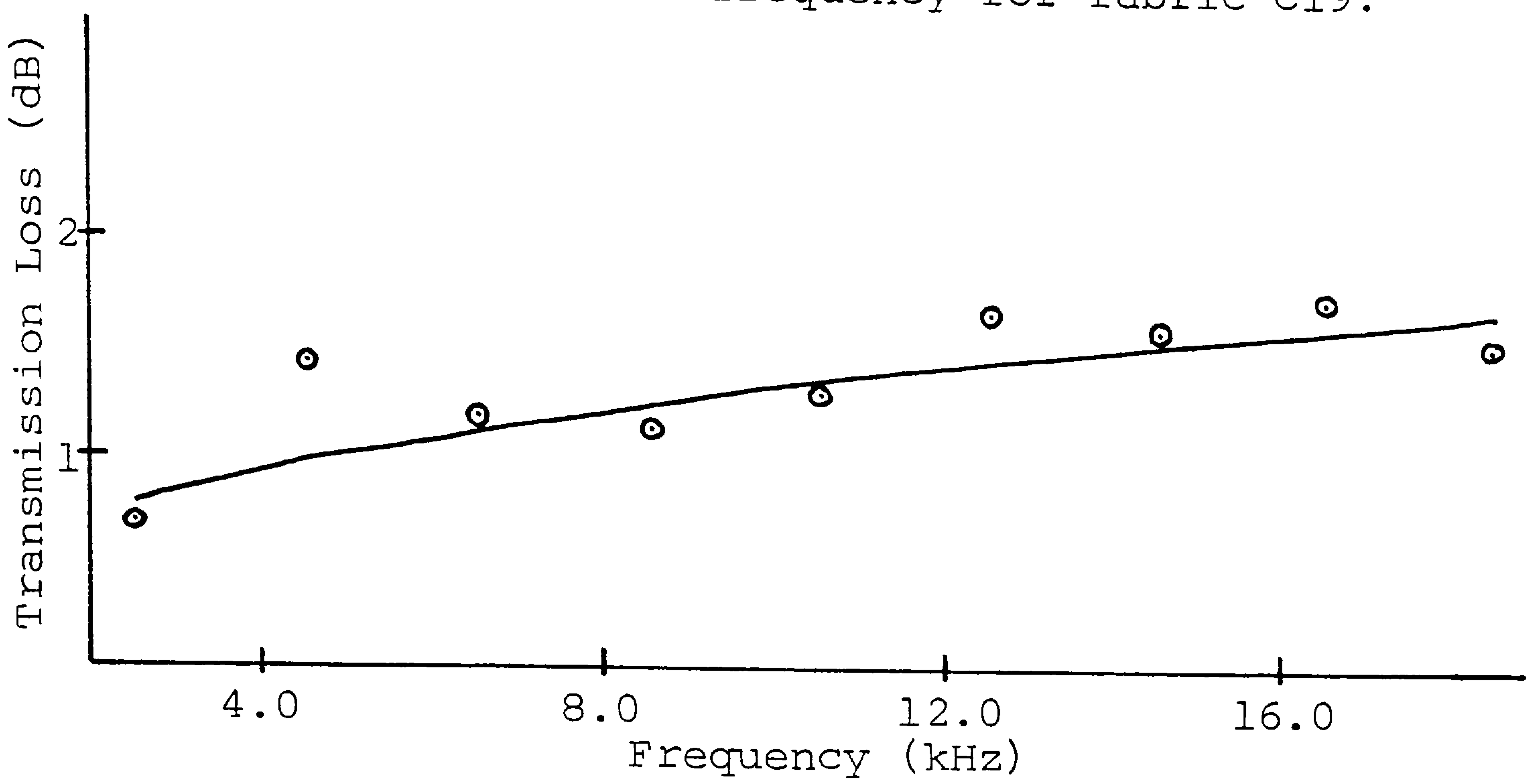


Figure A2.39 Experimental and theoretical transmission loss versus frequency for fabric C20.

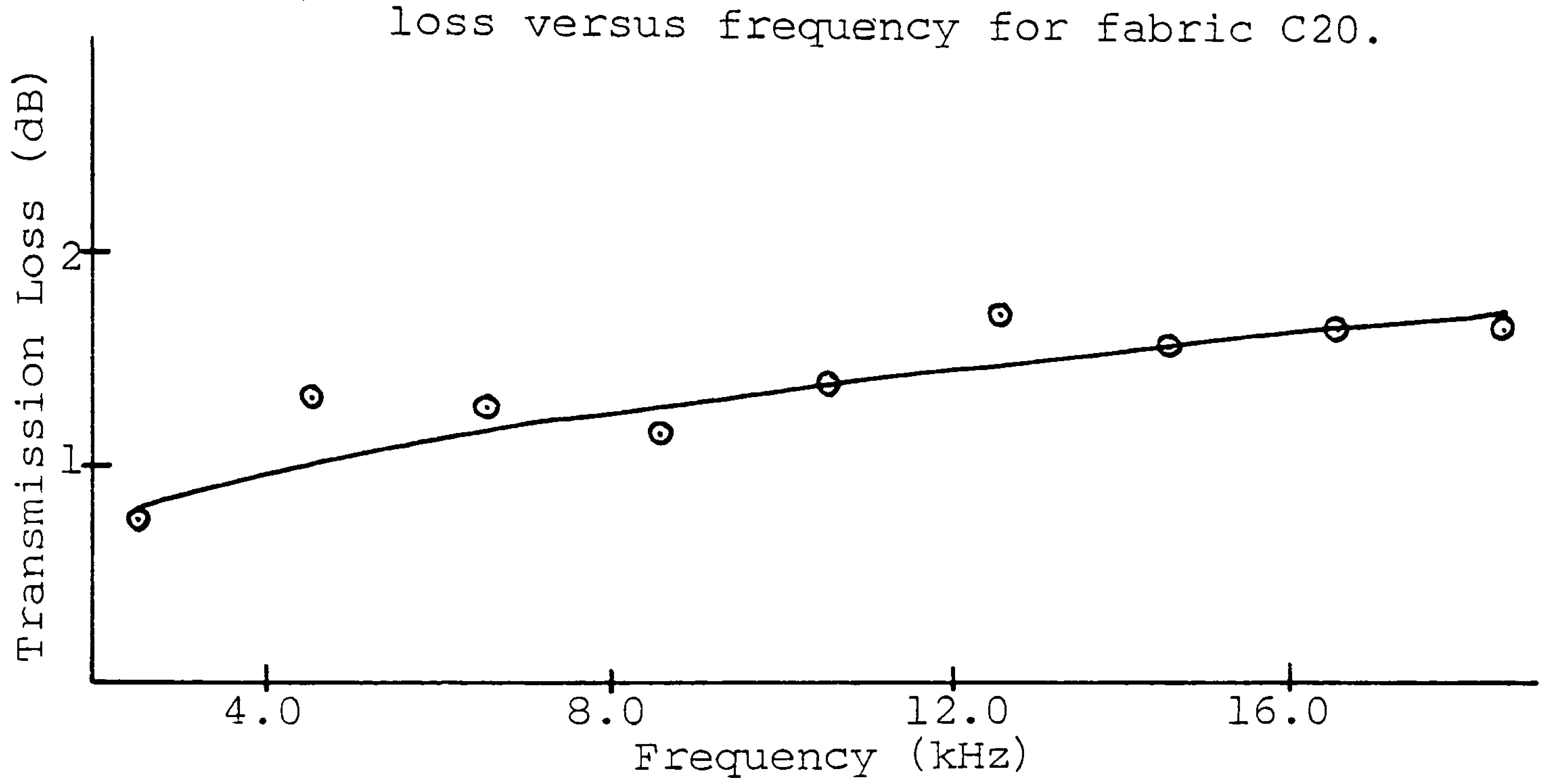


Figure A2.40 Experimental and theoretical transmission loss versus frequency for fabric C21.

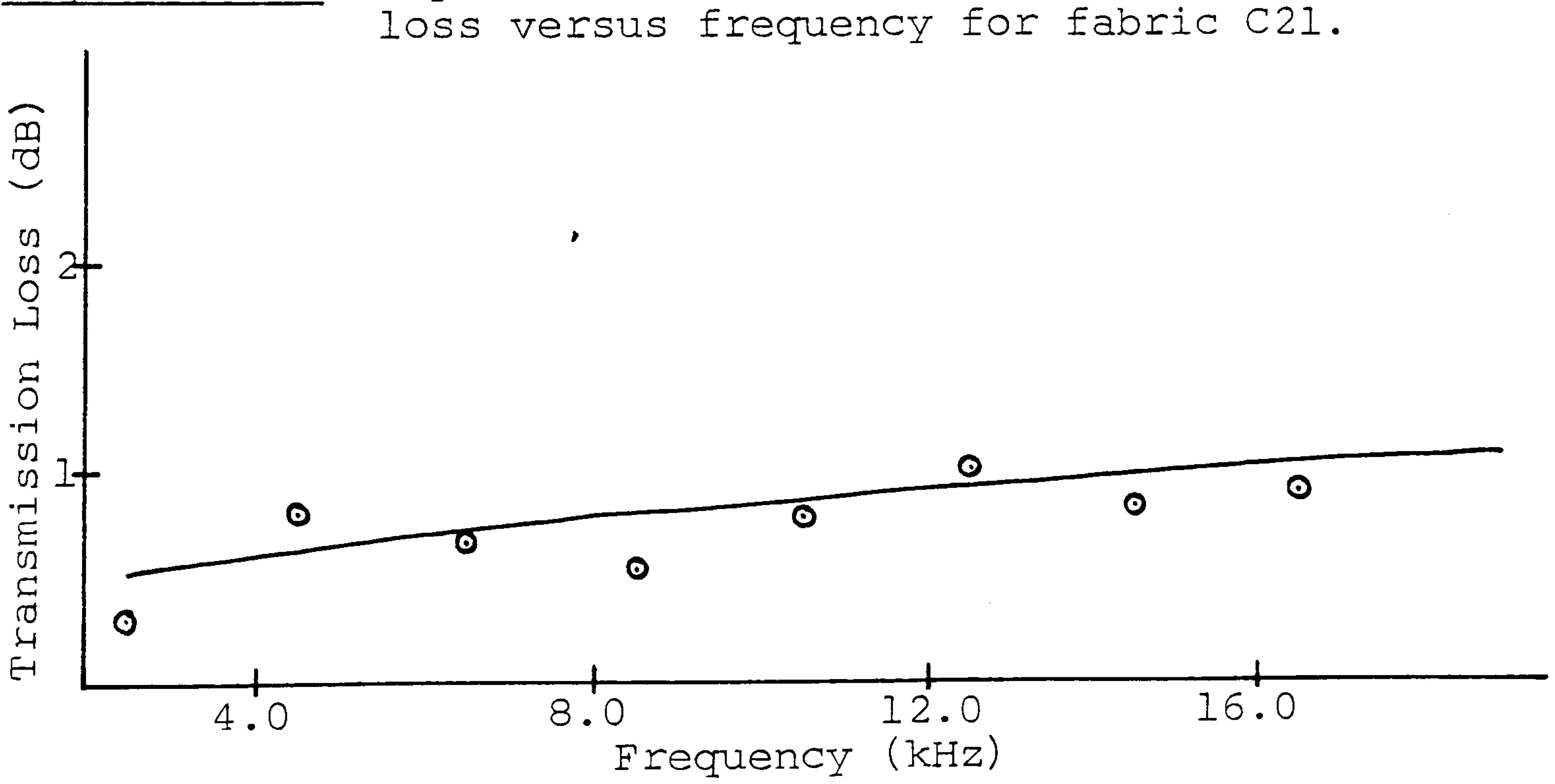


Figure A2.41 Experimental and theoretical transmission loss versus frequency for fabric C22.

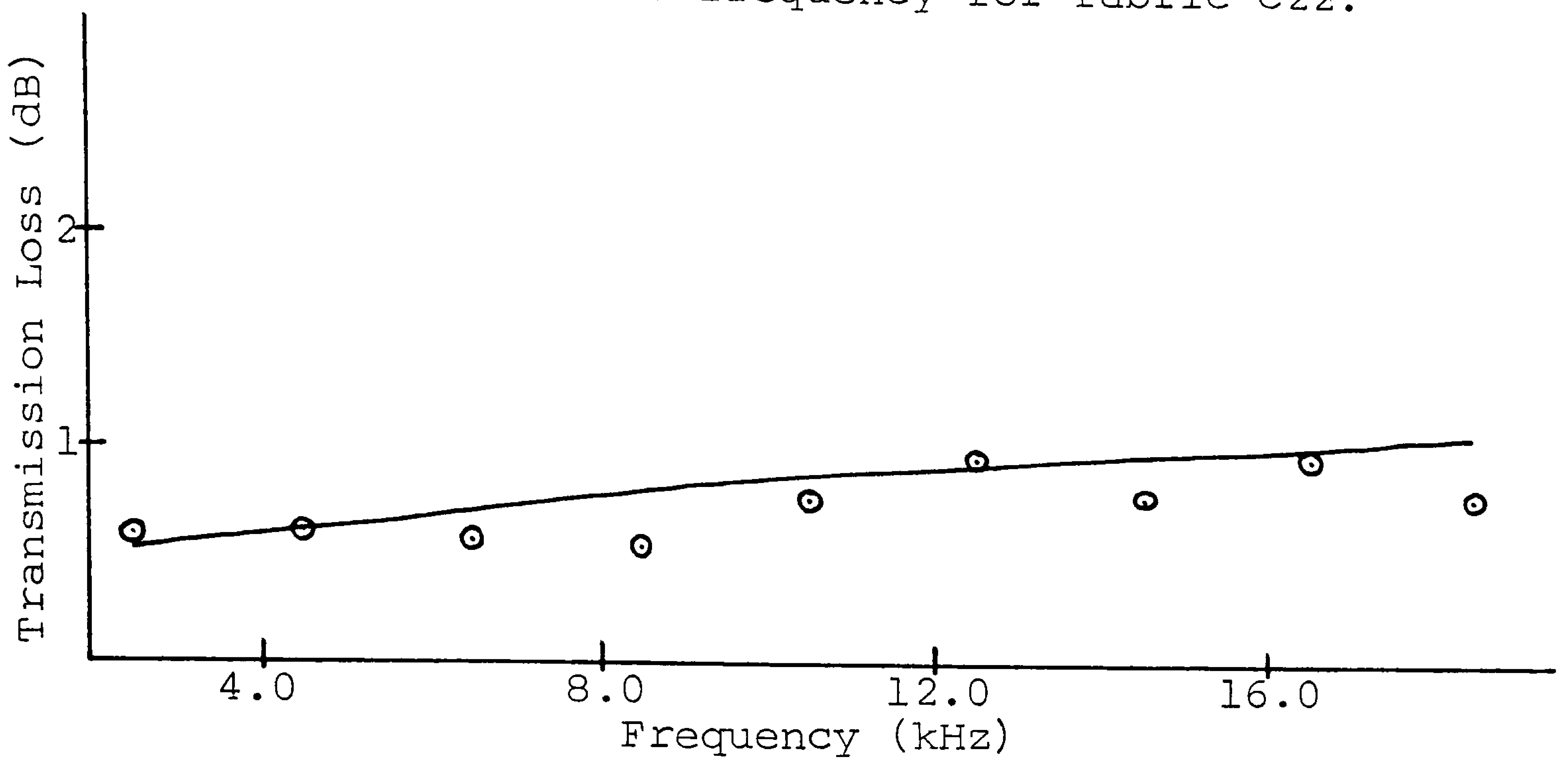


Figure A2.42 Experimental and theoretical transmission loss versus frequency for fabric C23.

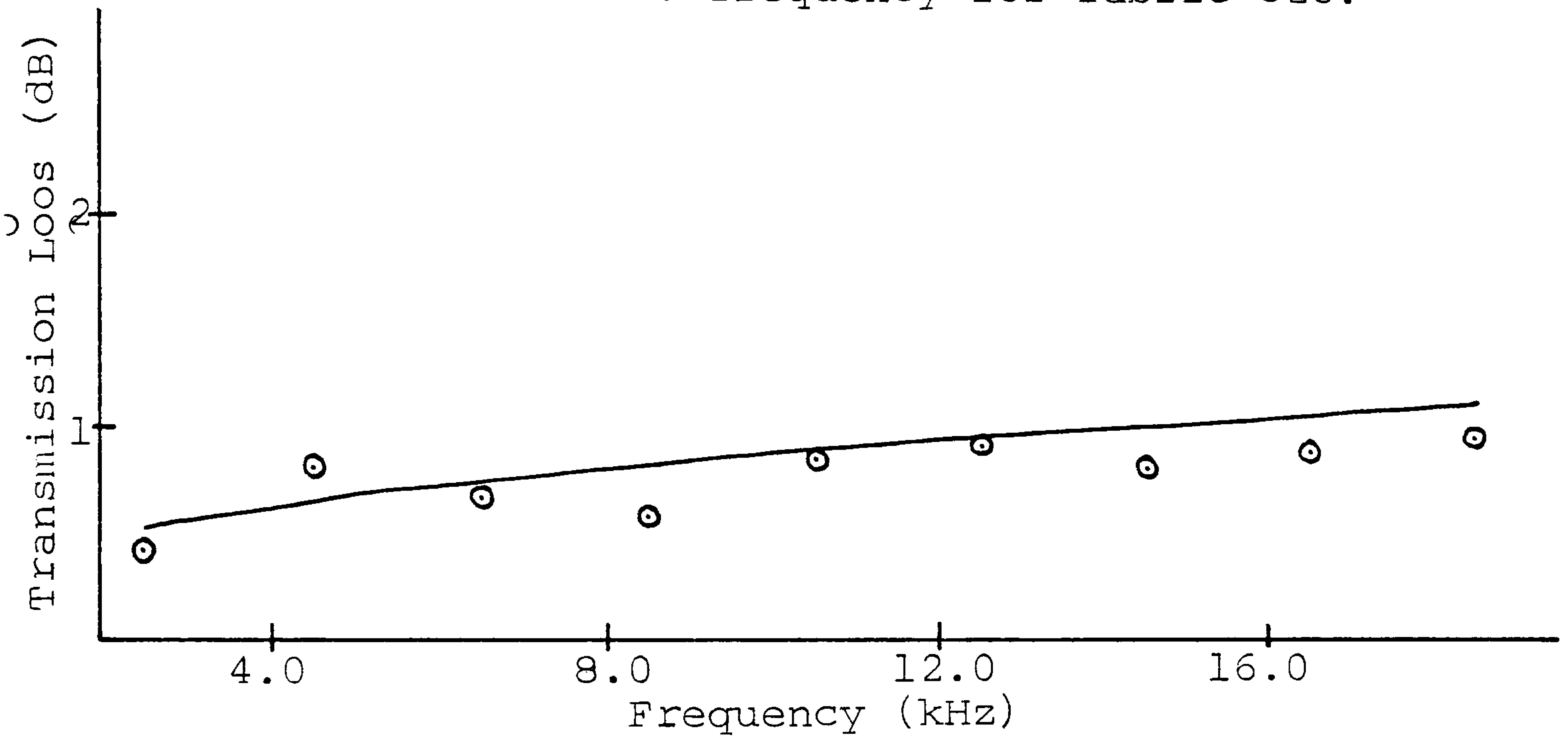


Figure A2. 43 Experimental and theoretical transmission loss versus frequency for fabric C24.

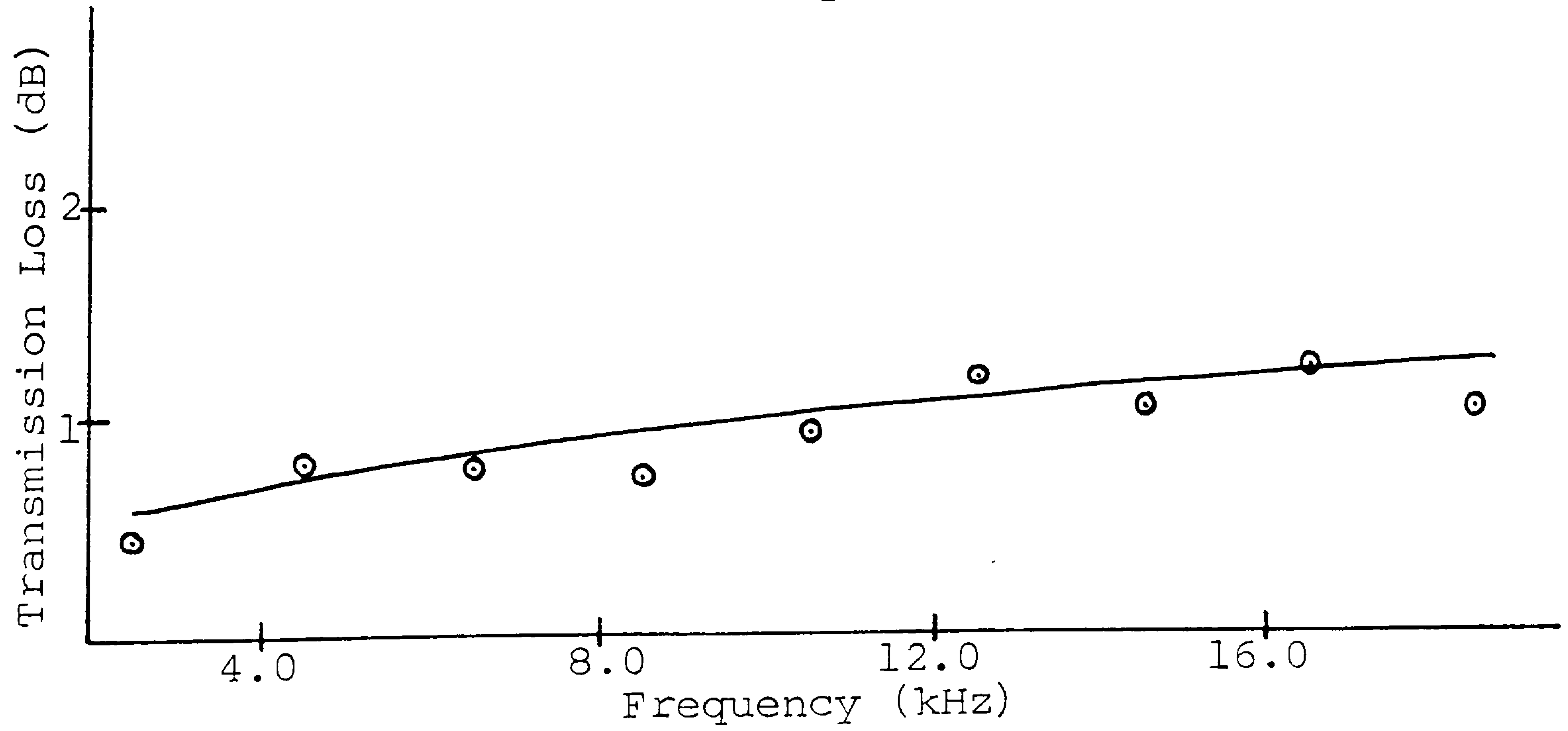


Figure A2.44 Experimental and theoretical transmission loss versus frequency for fabric C25.

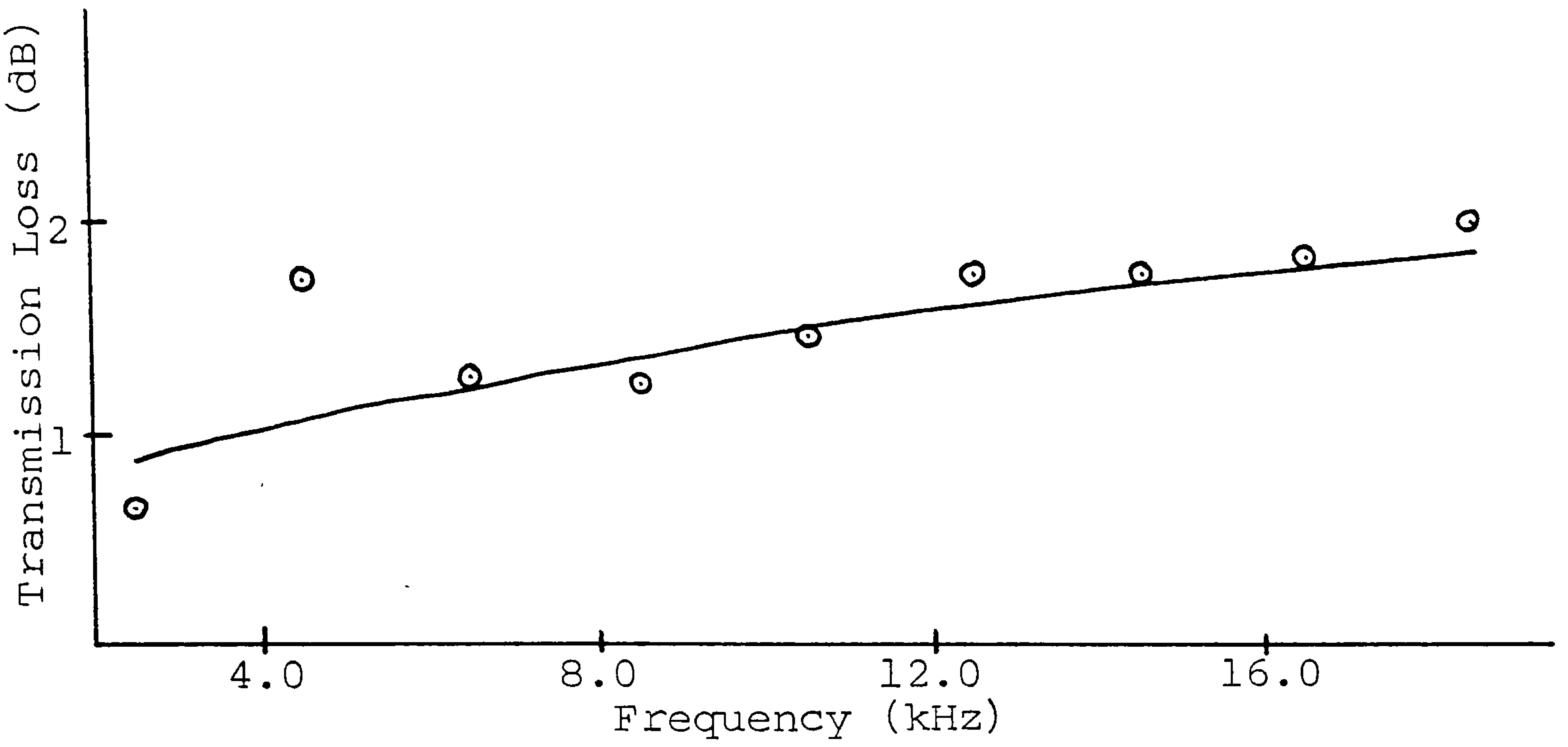


Figure A2.45 Experimental and theoretical transmission loss versus frequency for fabric C26.

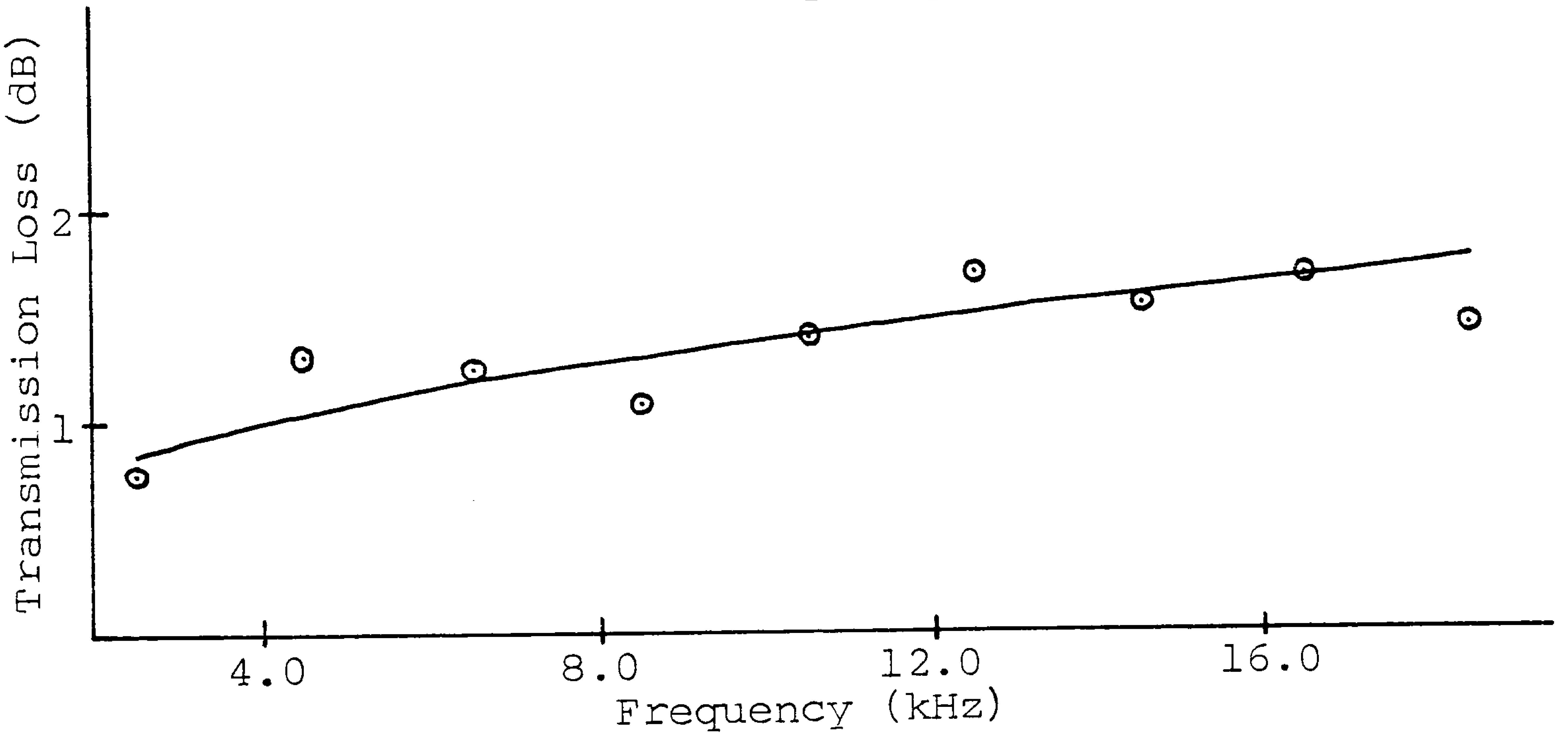


Figure A2.46 Experimental and theoretical transmission loss versus frequency for fabric C27.

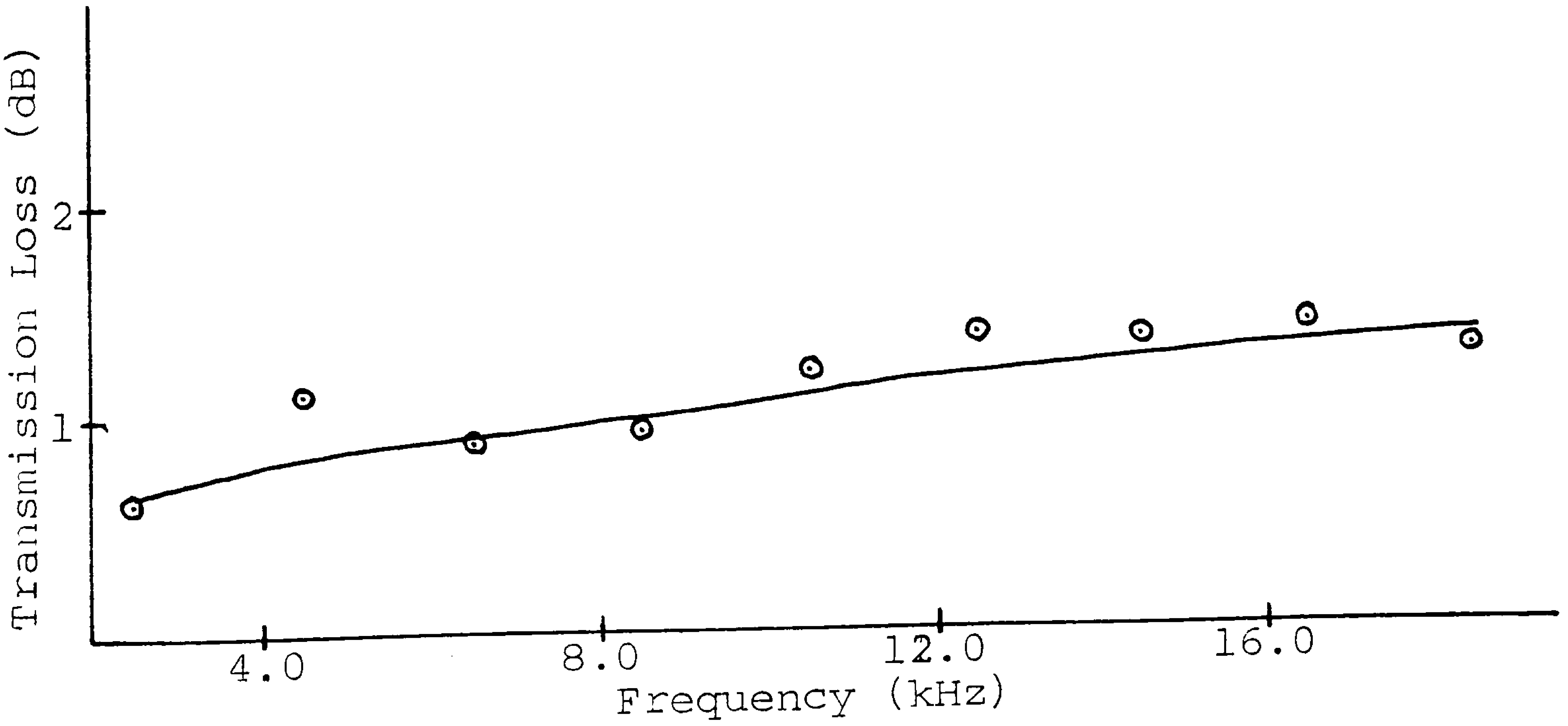


Figure A2.47 Experimental and theoretical transmission loss versus frequency for fabric C28.

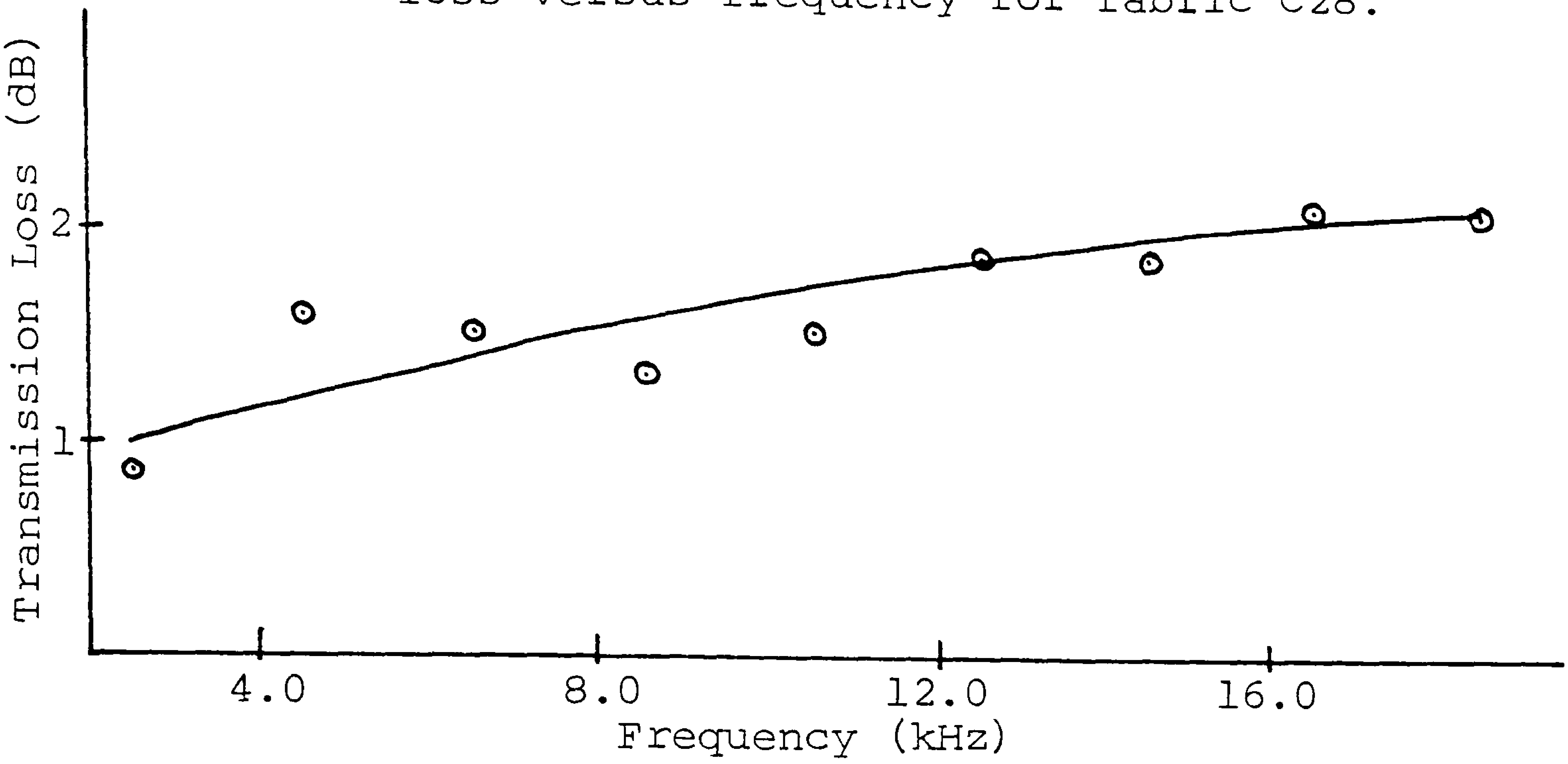


Figure A2.48 Experimental and theoretical transmission loss versus frequency for fabric C29.

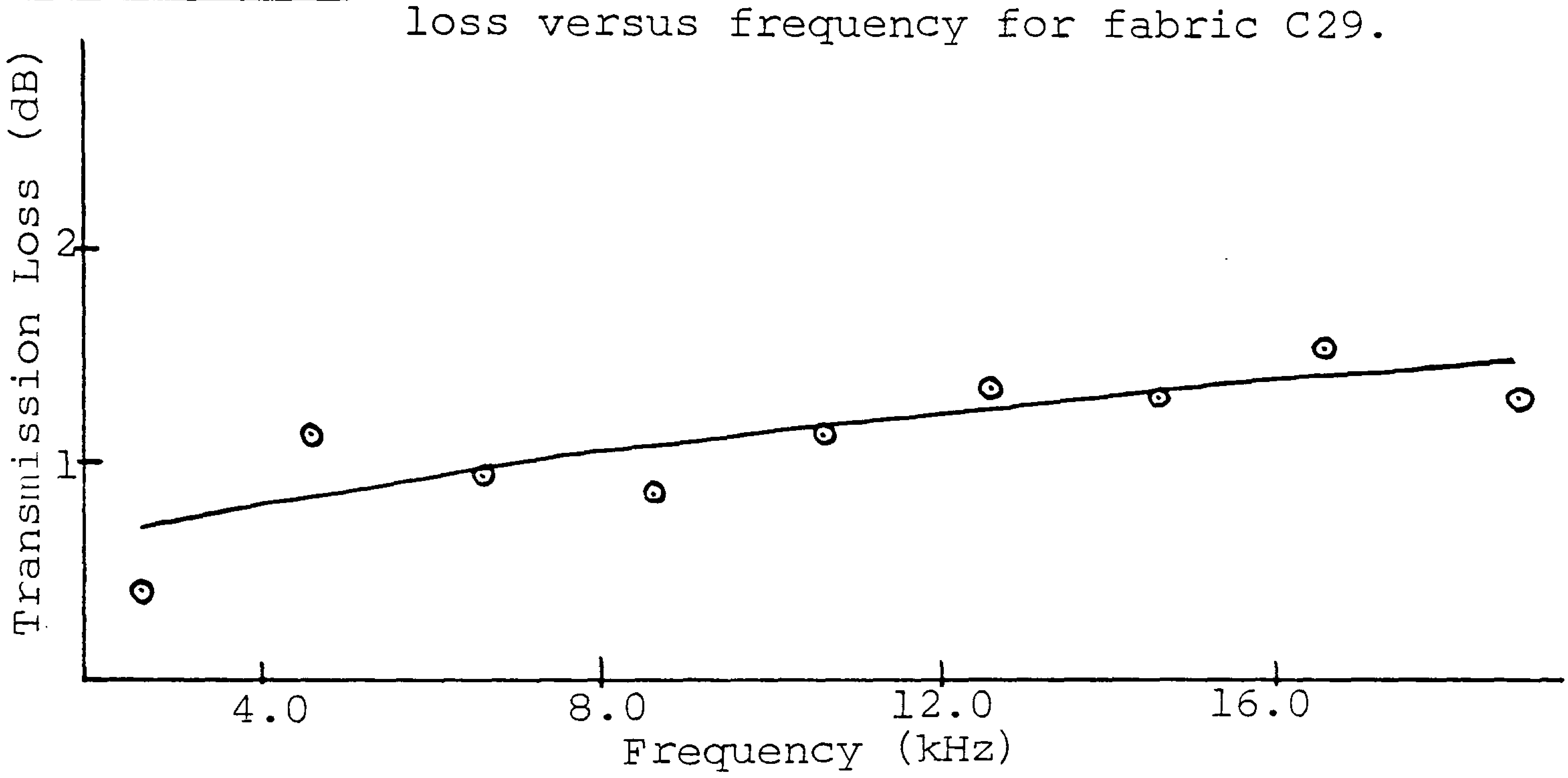


Figure A2.49 Experimental and theoretical transmission loss versus frequency for fabric C30.

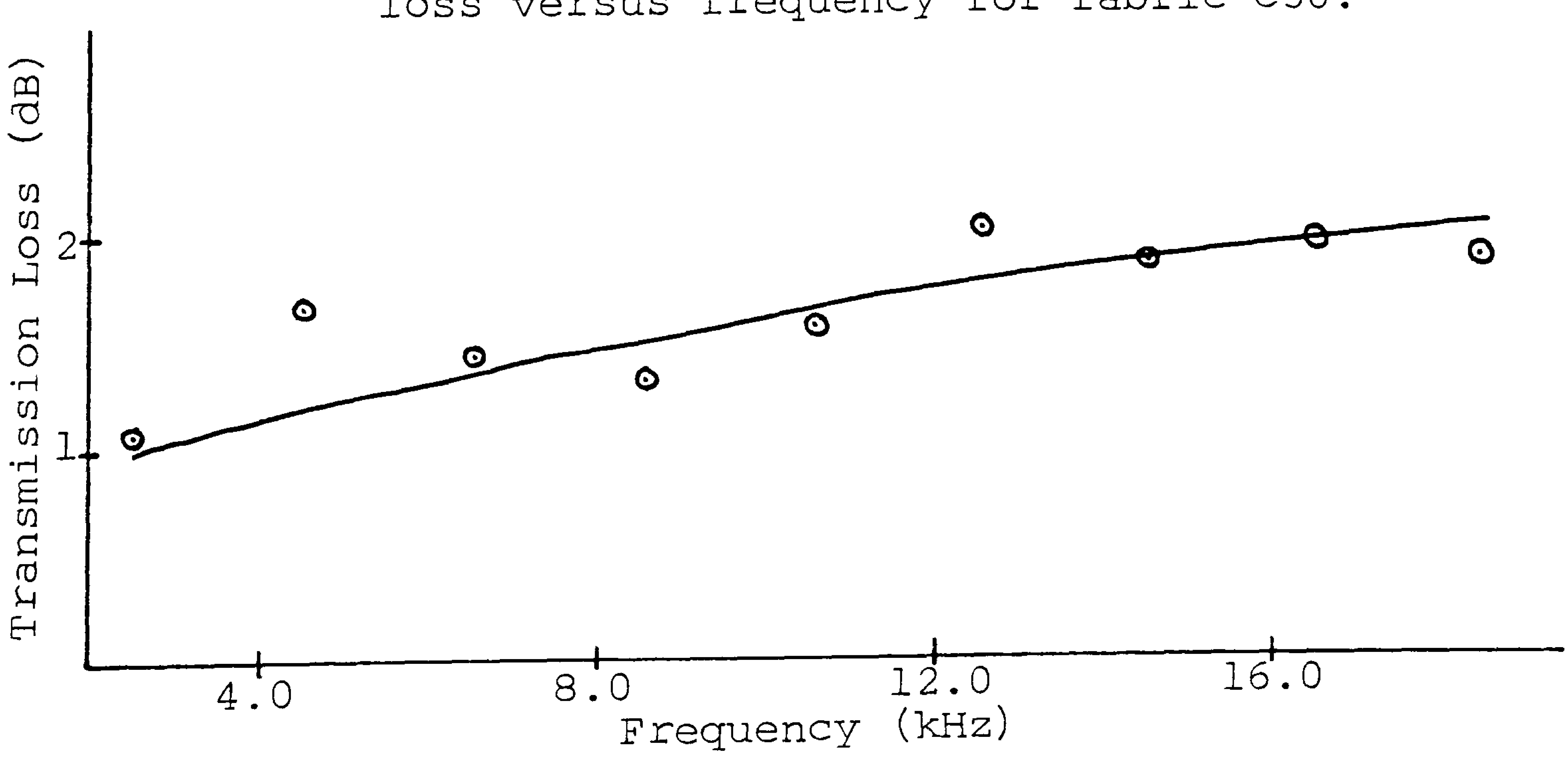


Figure A2.50 Experimental and theoretical transmission loss versus frequency for fabric C31.

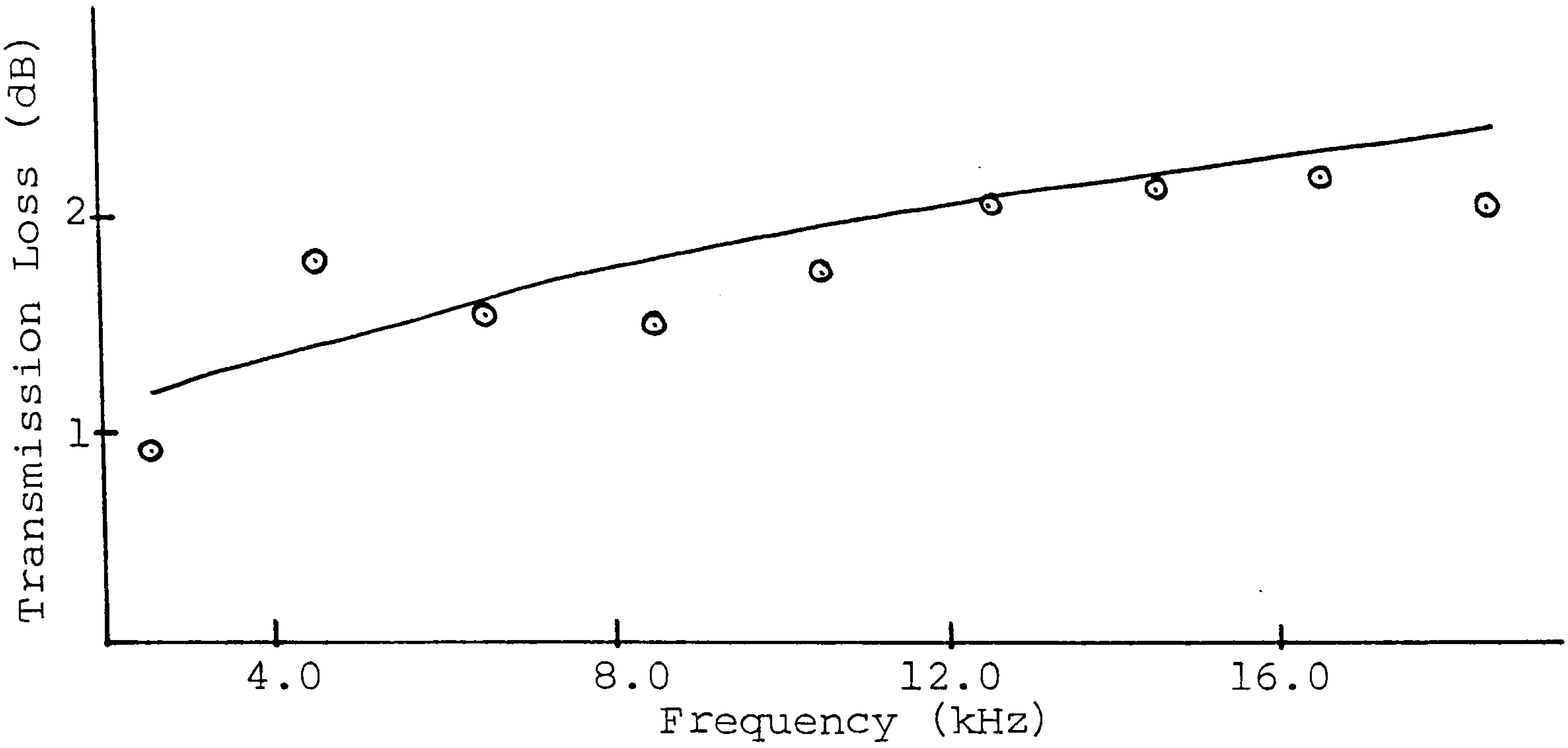


Figure A2.51 Experimental and theoretical transmission loss versus frequency for fabric C32.

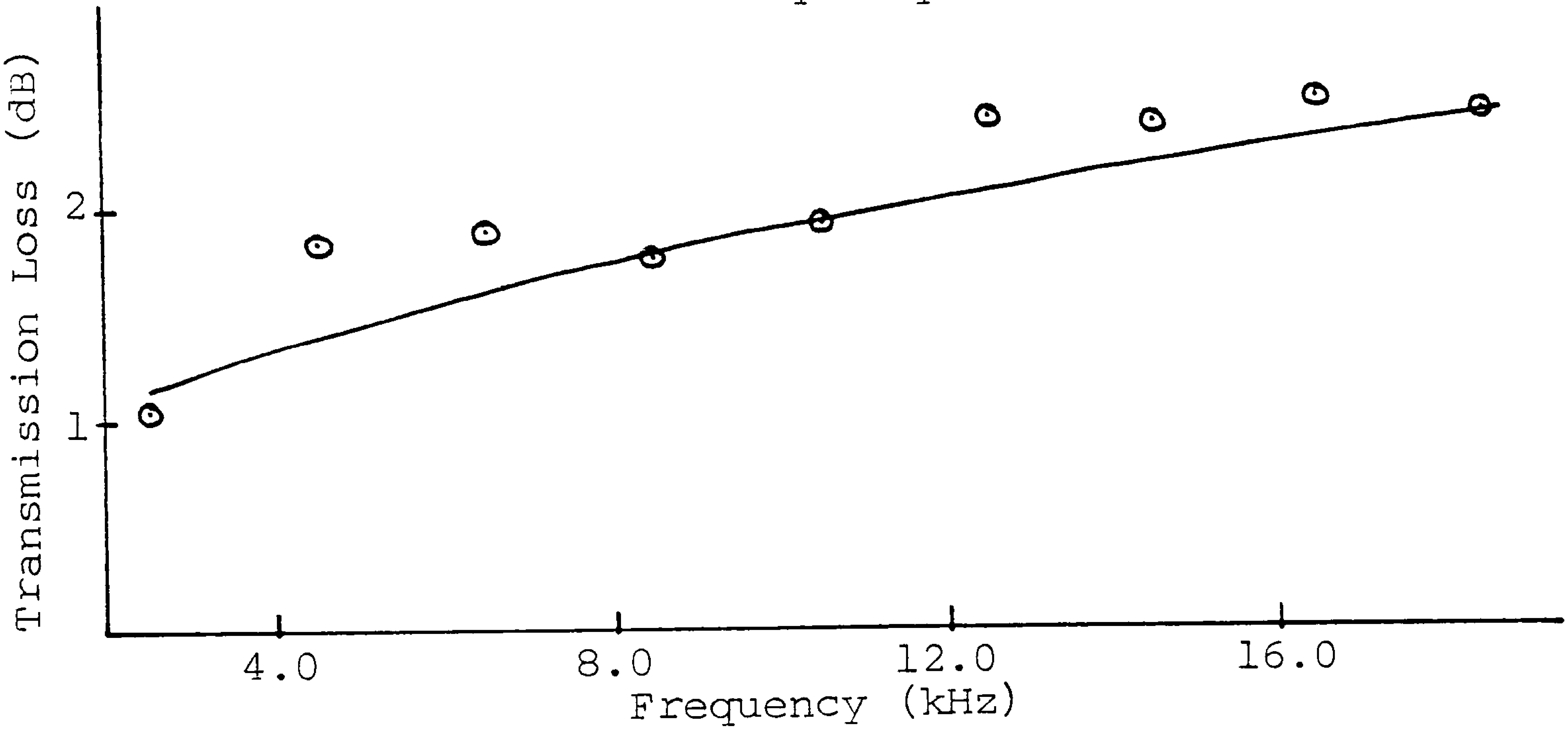


Figure A2.52 Experimental and theoretical transmission loss versus frequency for fabric C33.

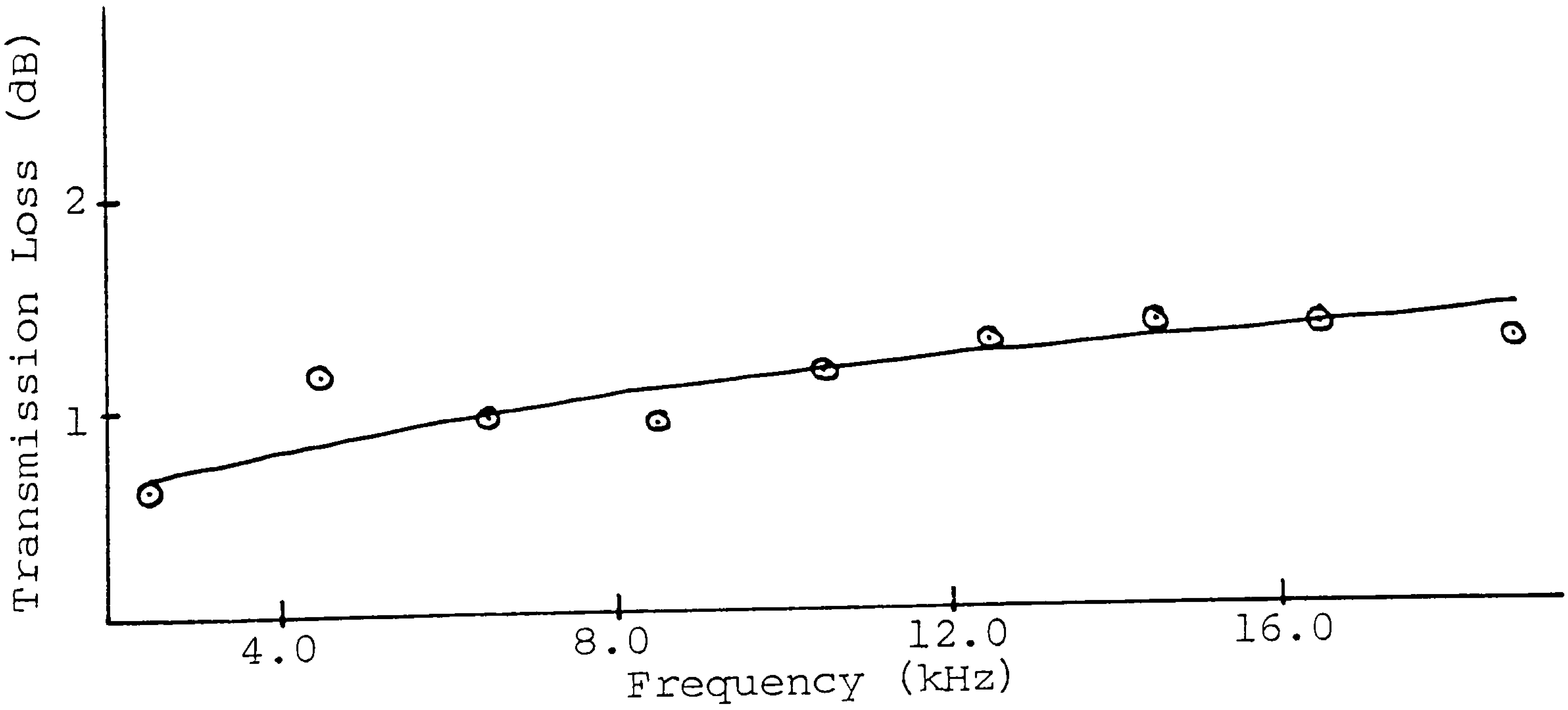


Figure A2.53 Experimental and theoretical transmission loss versus frequency for fabric C34.

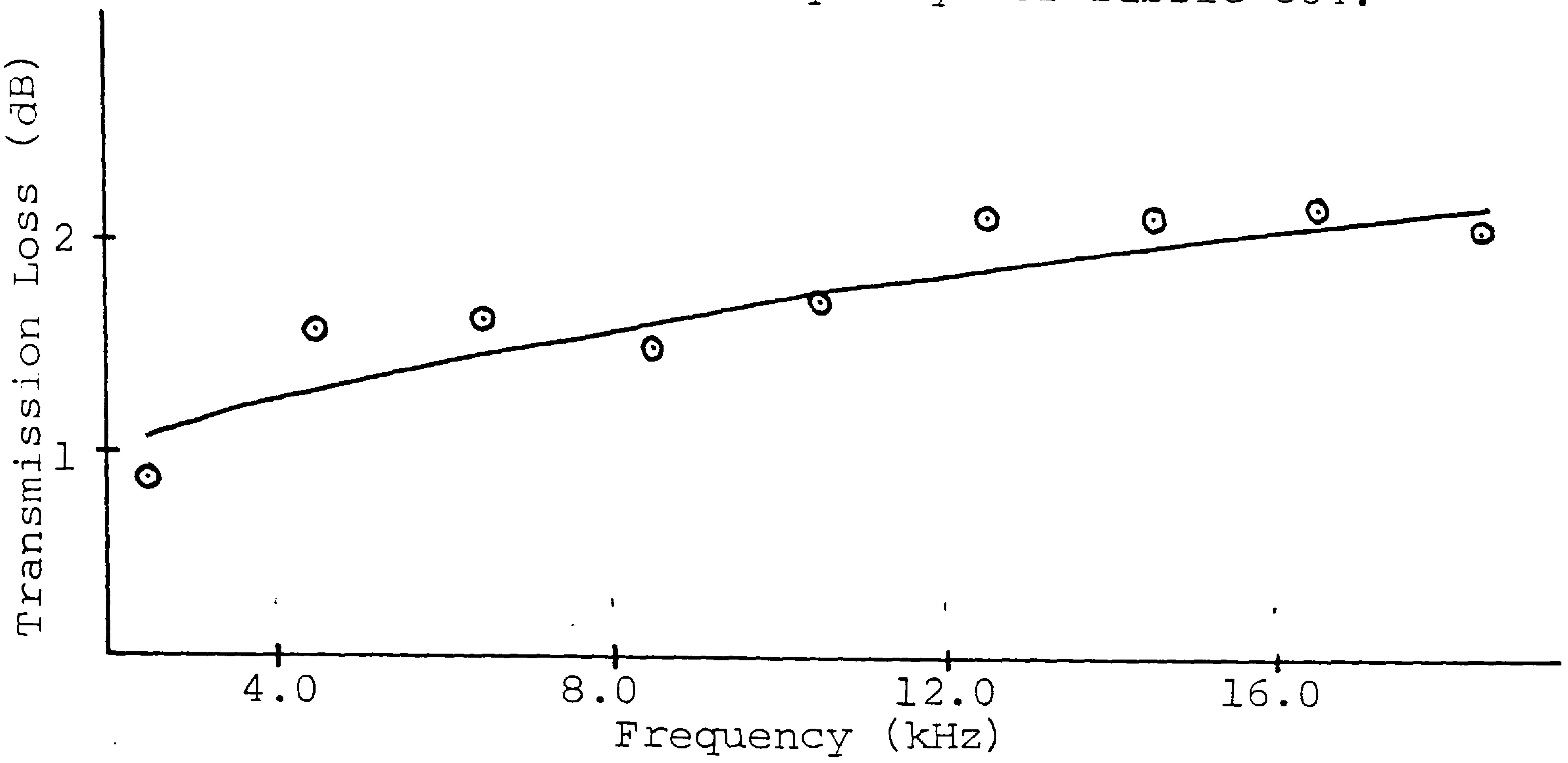


Figure A2.54 Experimental and theoretical transmission loss versus frequency for fabric C35.

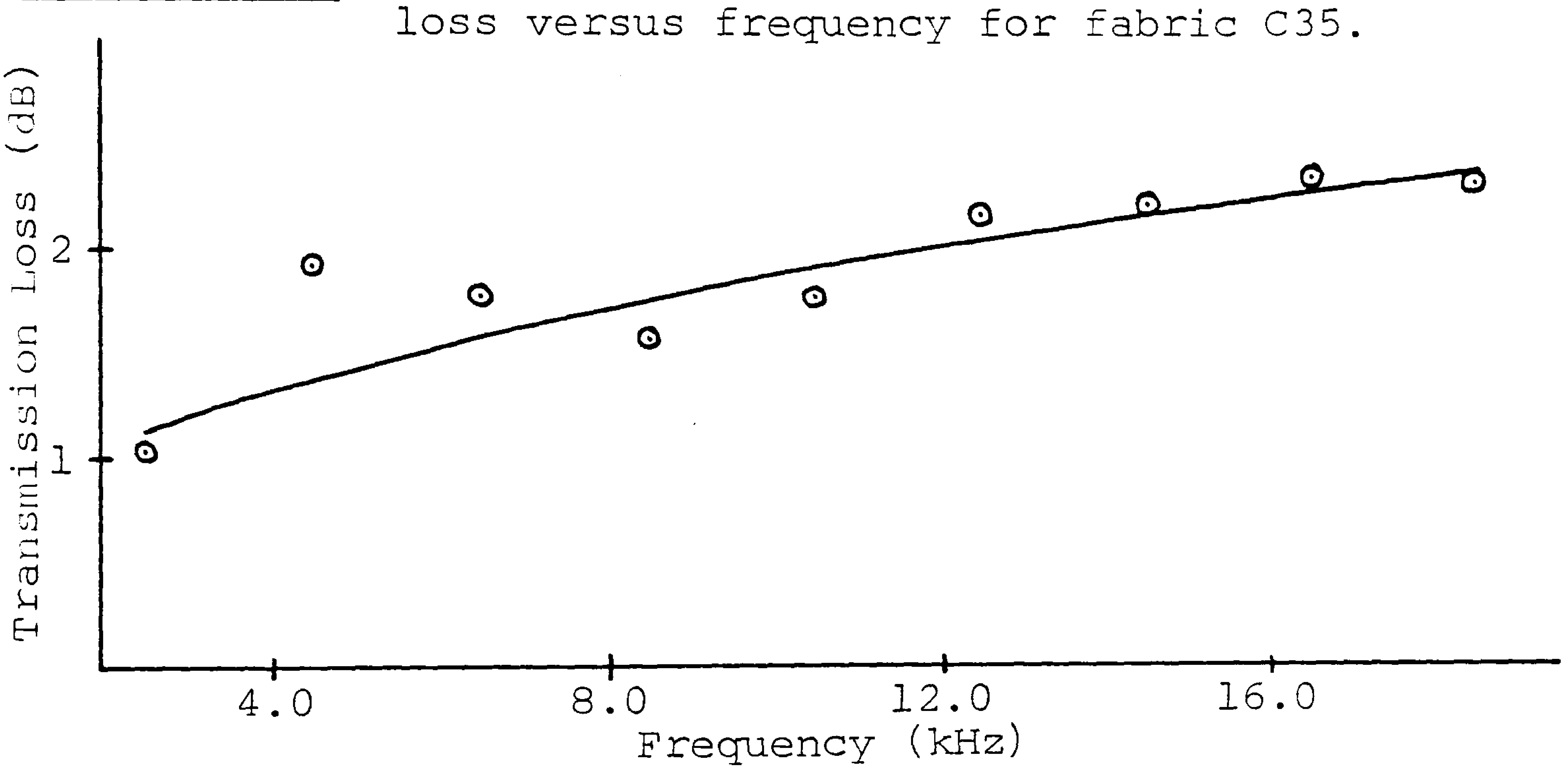


Figure A2.55 Experimental and theoretical transmission loss versus frequency for fabric C36.

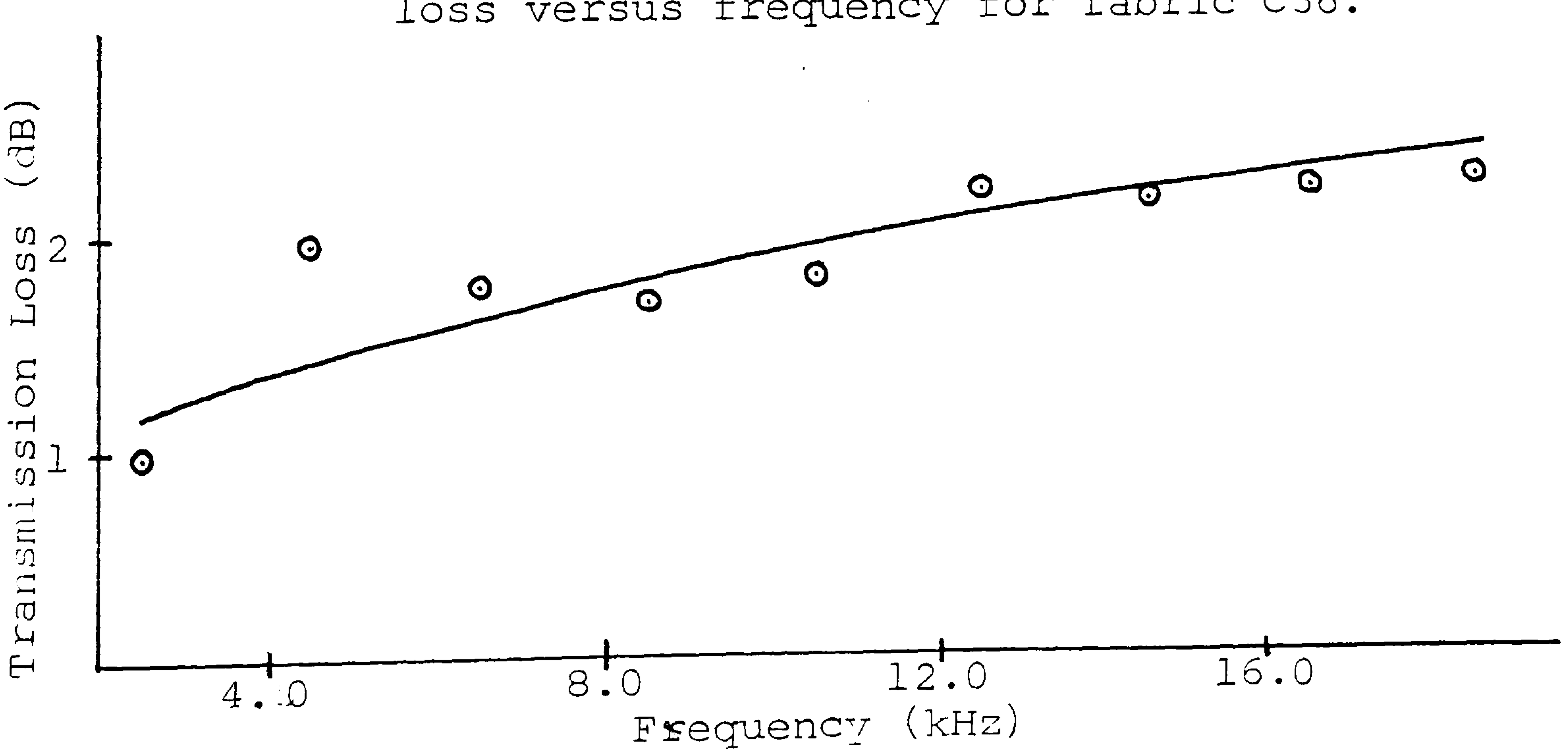


Figure A2.56 Experimental and theoretical transmission loss versus frequency for fabric D1.

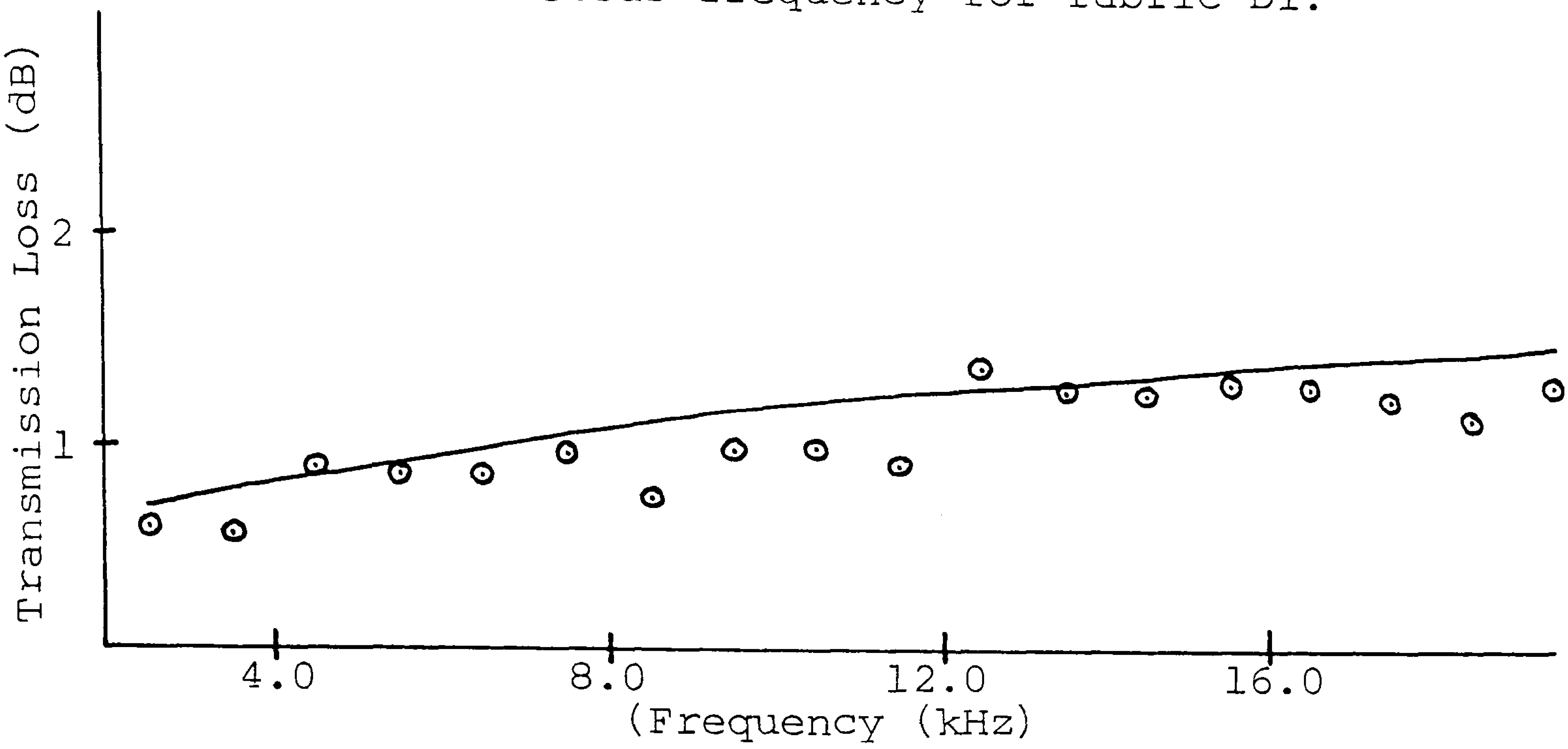


Figure A2.57 Experimental and theoretical transmission loss versus frequency for fabric D2.

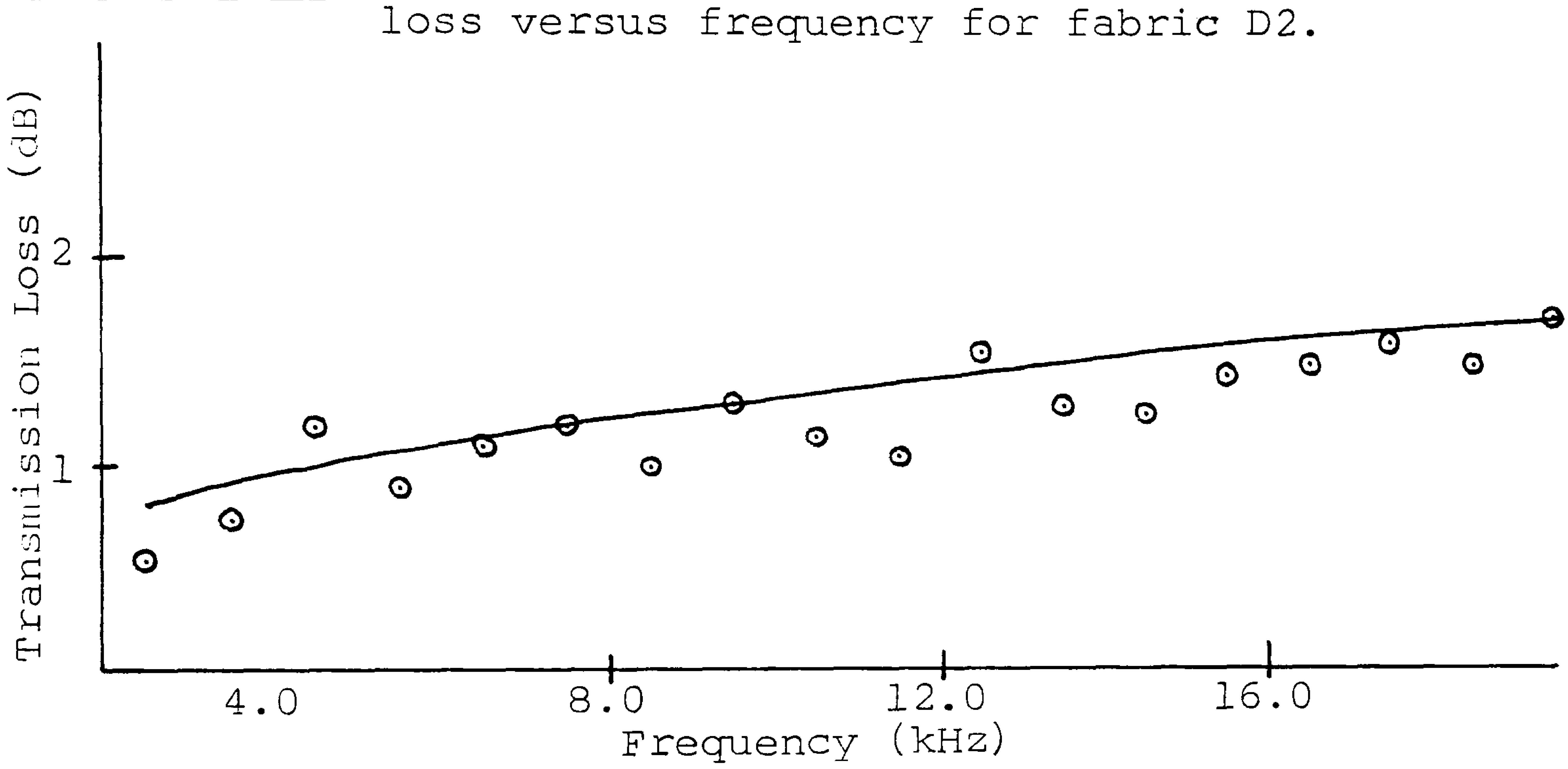


Figure A2.58 Experimental and theoretical transmission loss versus frequency for fabric D3.

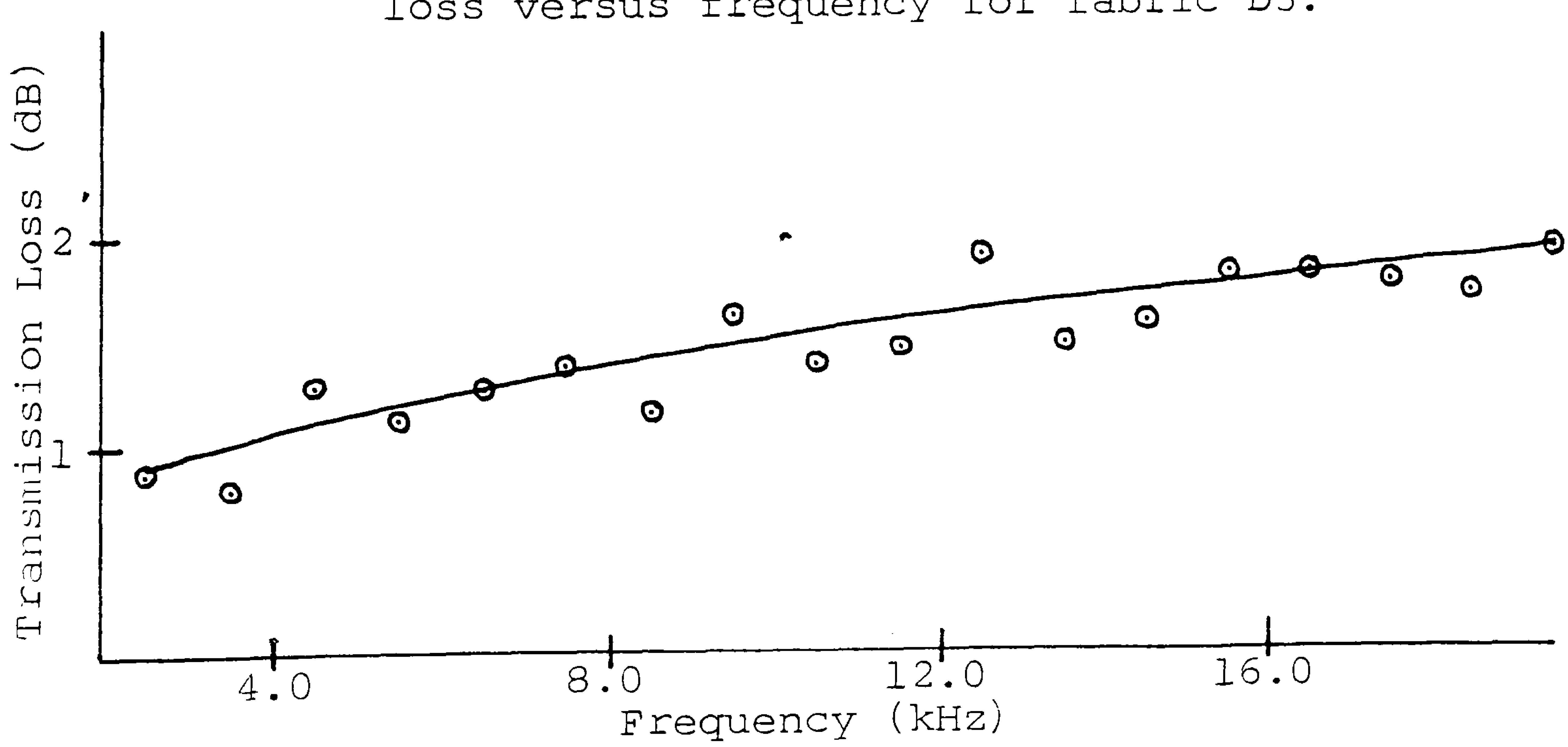


Figure A2.59 Experimental and theoretical transmission loss versus frequency for fabric D4.

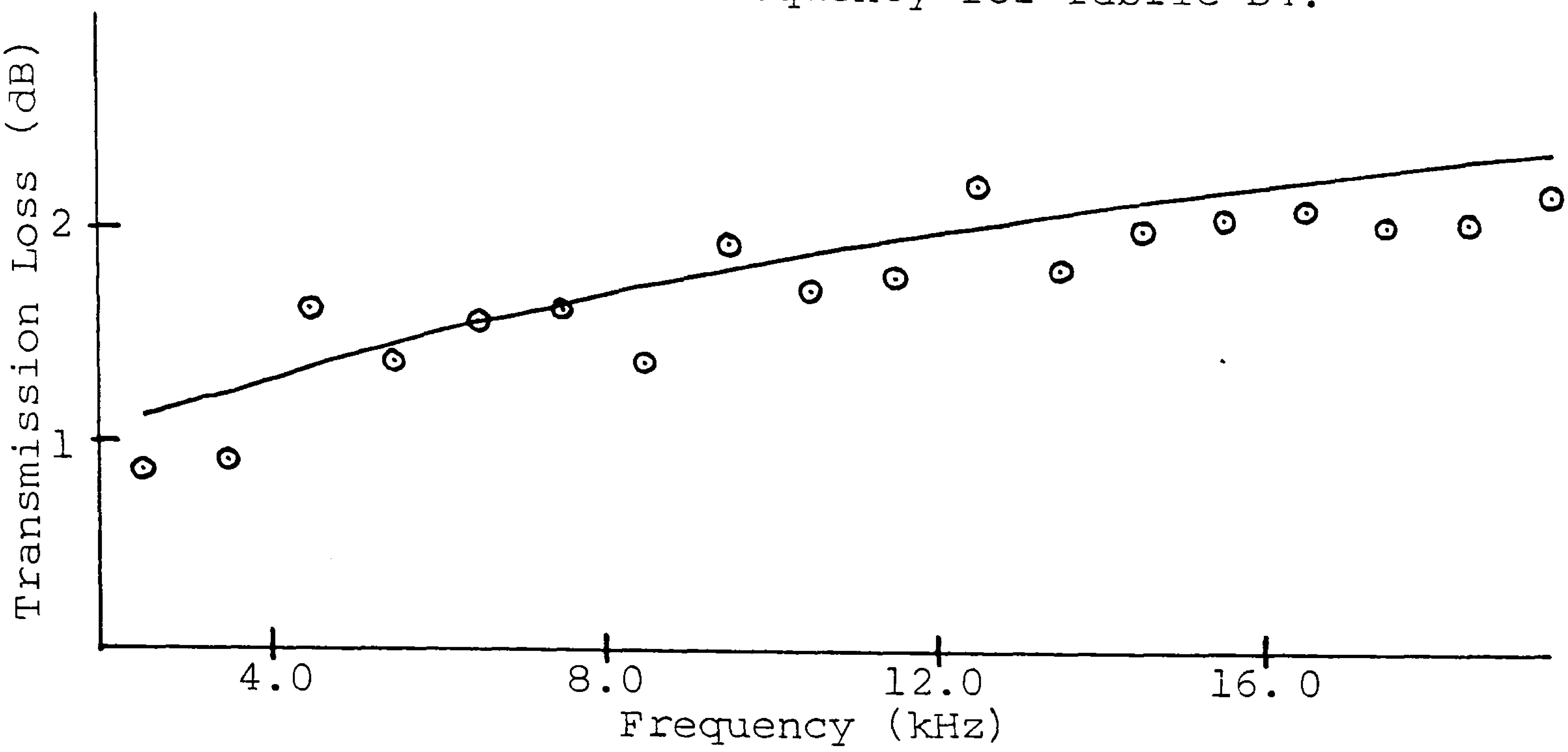


Figure A2.60 Experimental and theoretical transmission loss versus frequency for fabric D5.

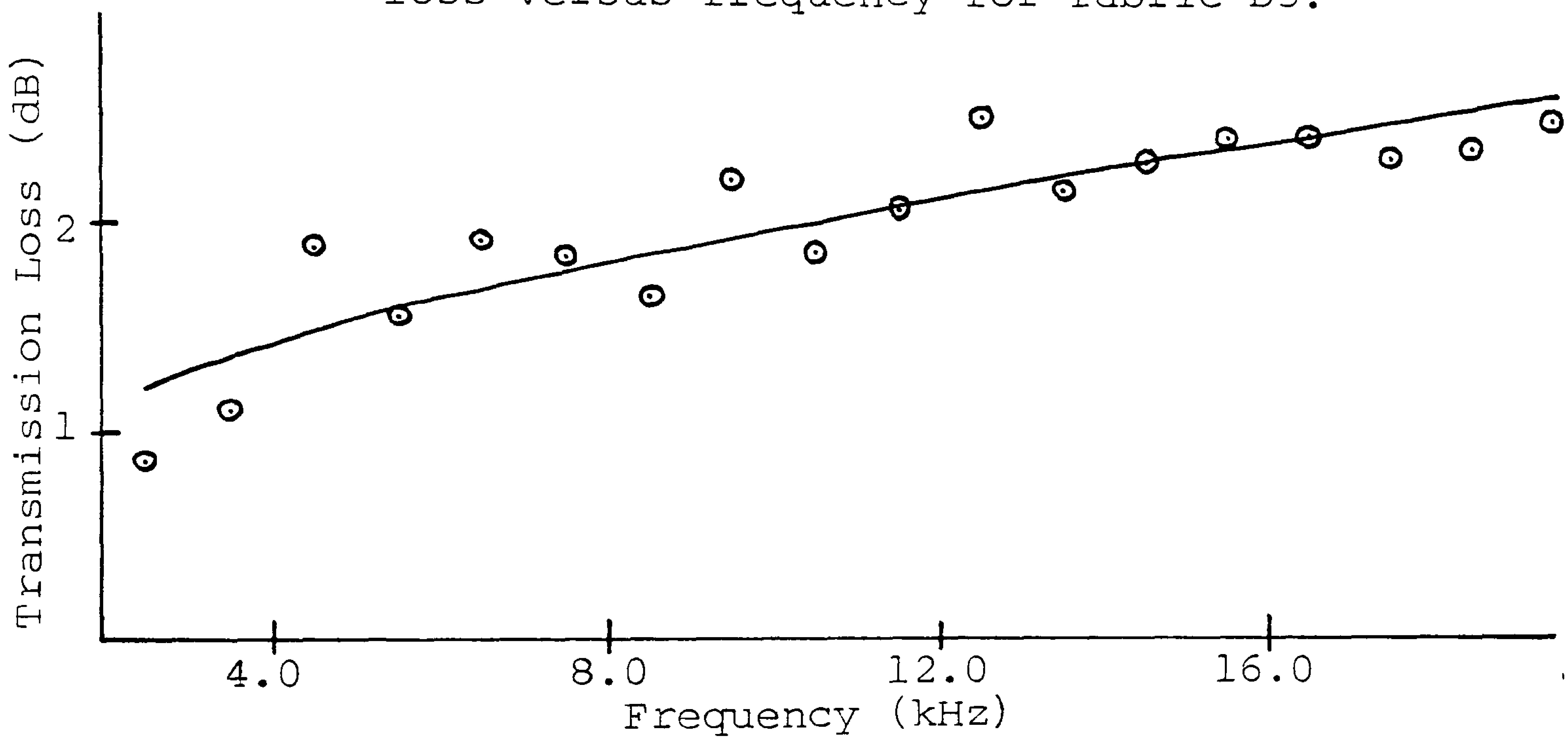


Figure A2.61. Experimental and theoretical transmission loss versus frequency for fabric D6.

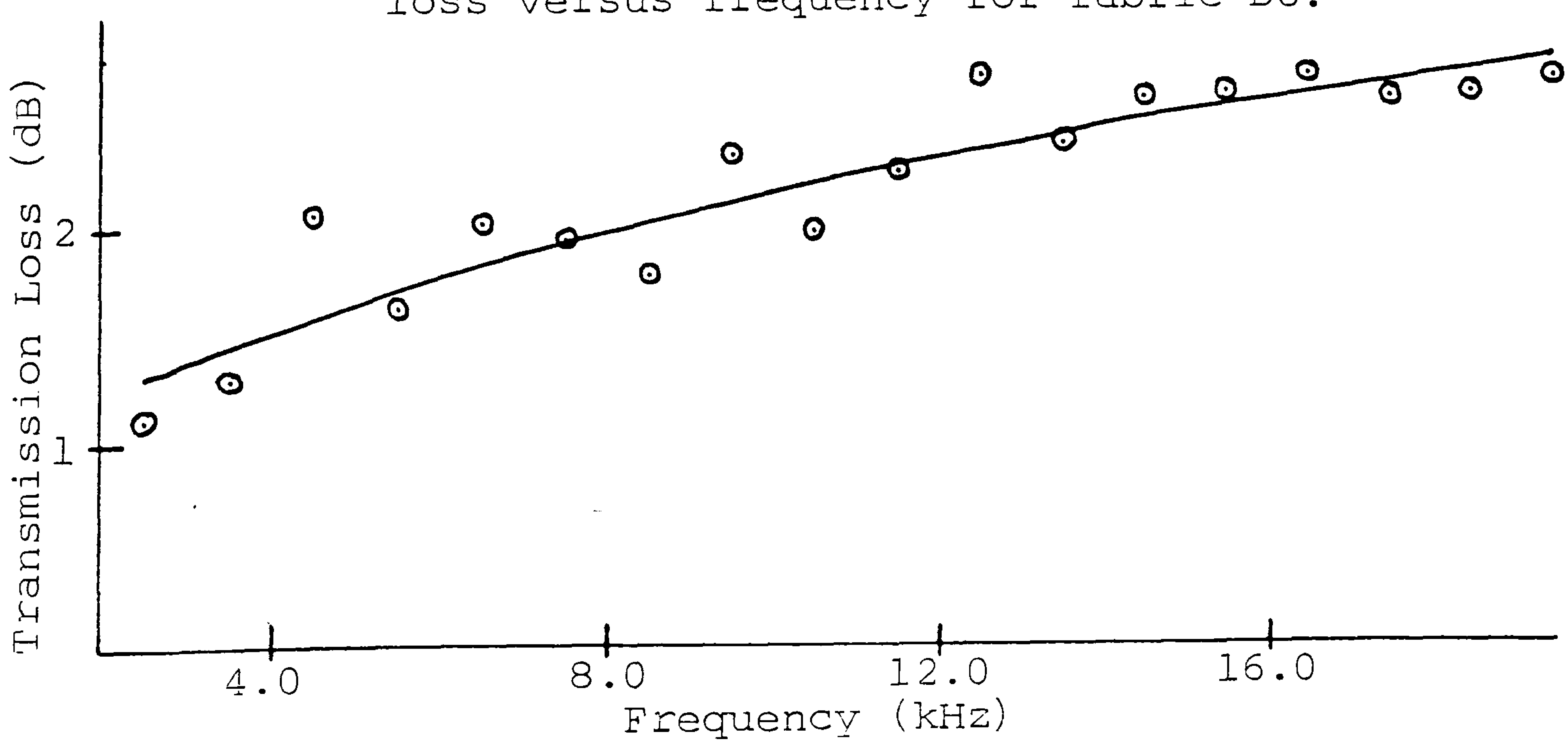


Figure A2.62 Experimental and theoretical transmission loss versus frequency for fabric D7.

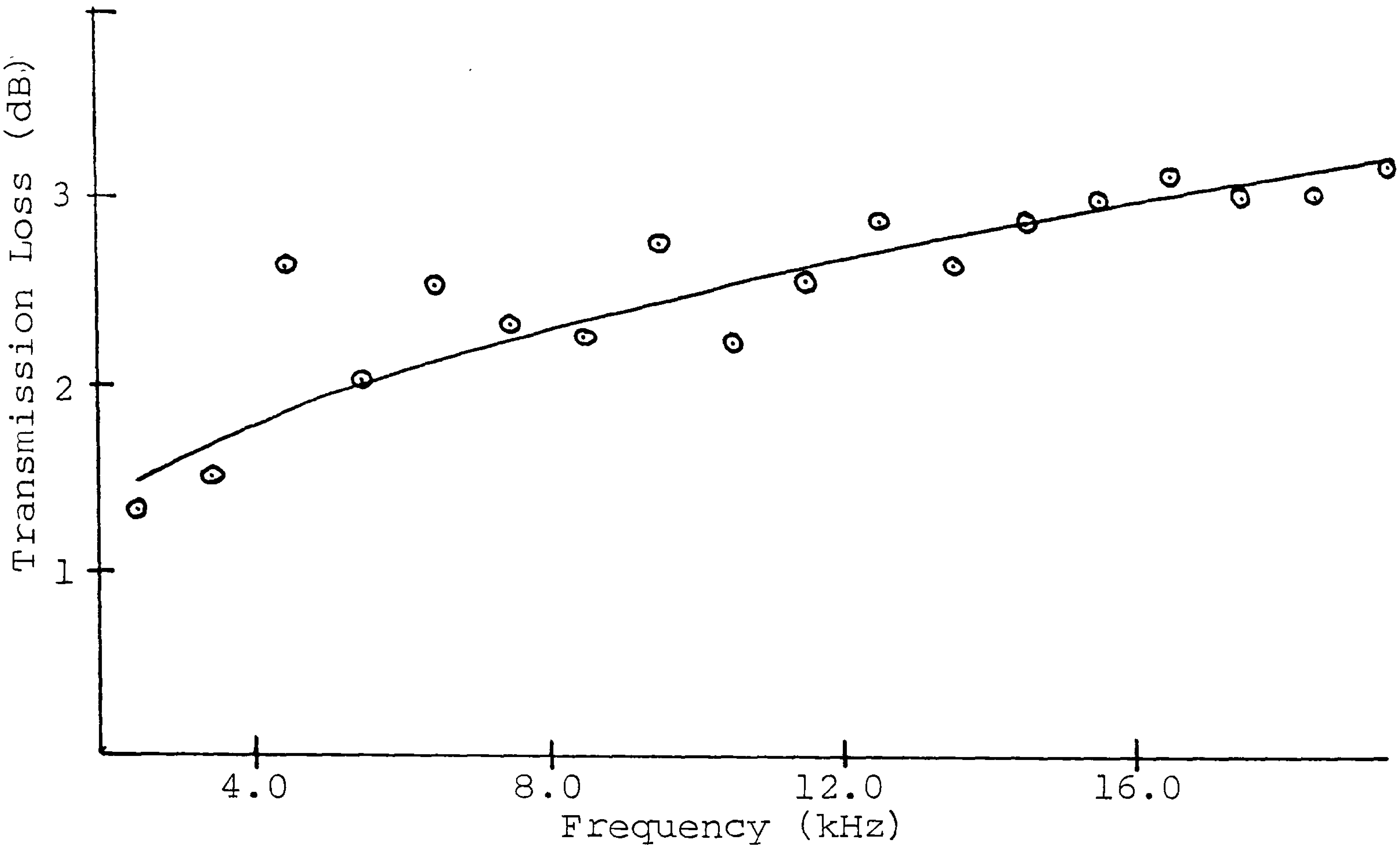


Figure A2.63 Experimental and theoretical transmission loss versus frequency for fabric E1.

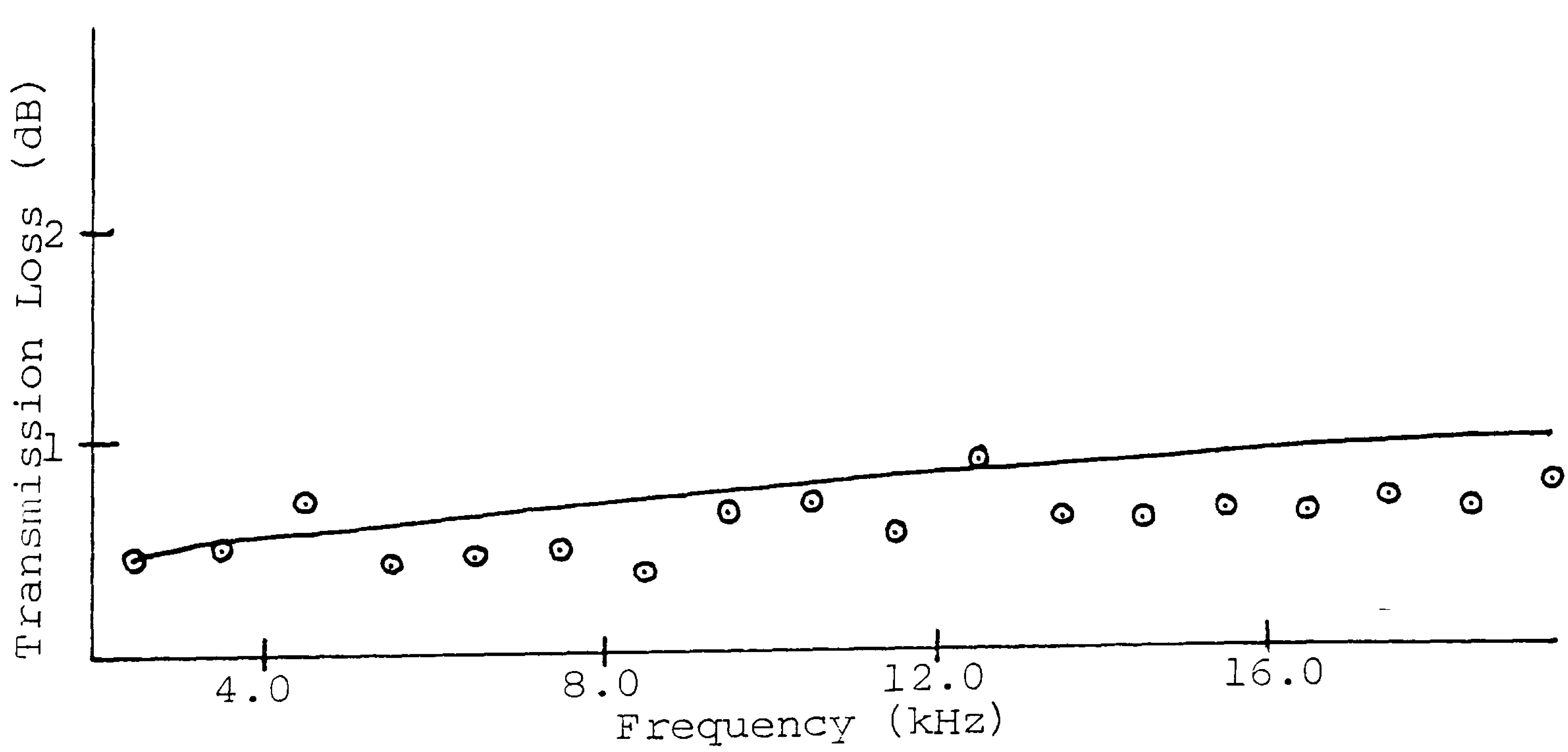


Figure A2.64 Experimental and theoretical transmission loss versus frequency for fabric E2.

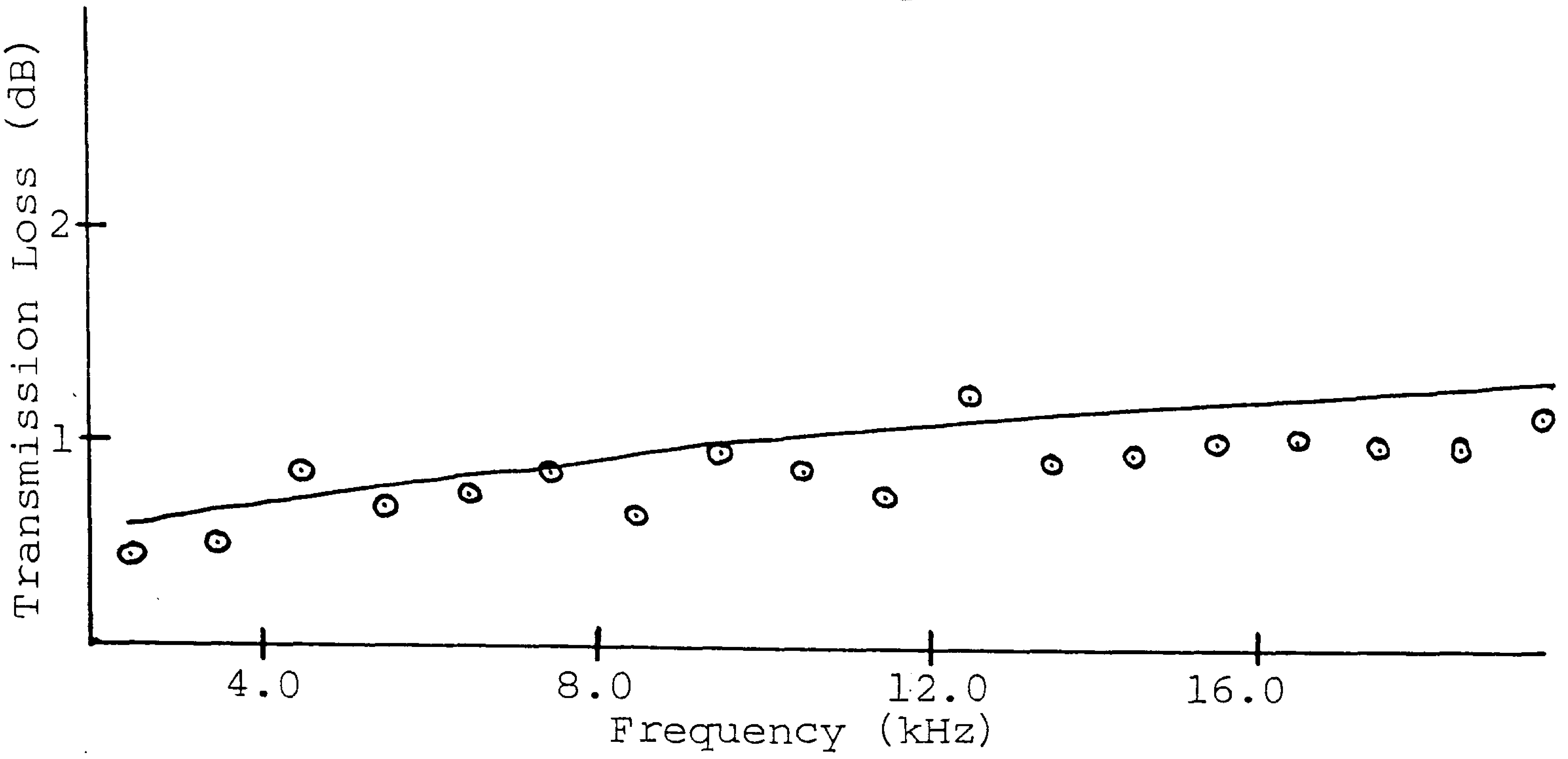


Figure A2.65 Experimental and theoretical transmission loss versus frequency for fabric E3.

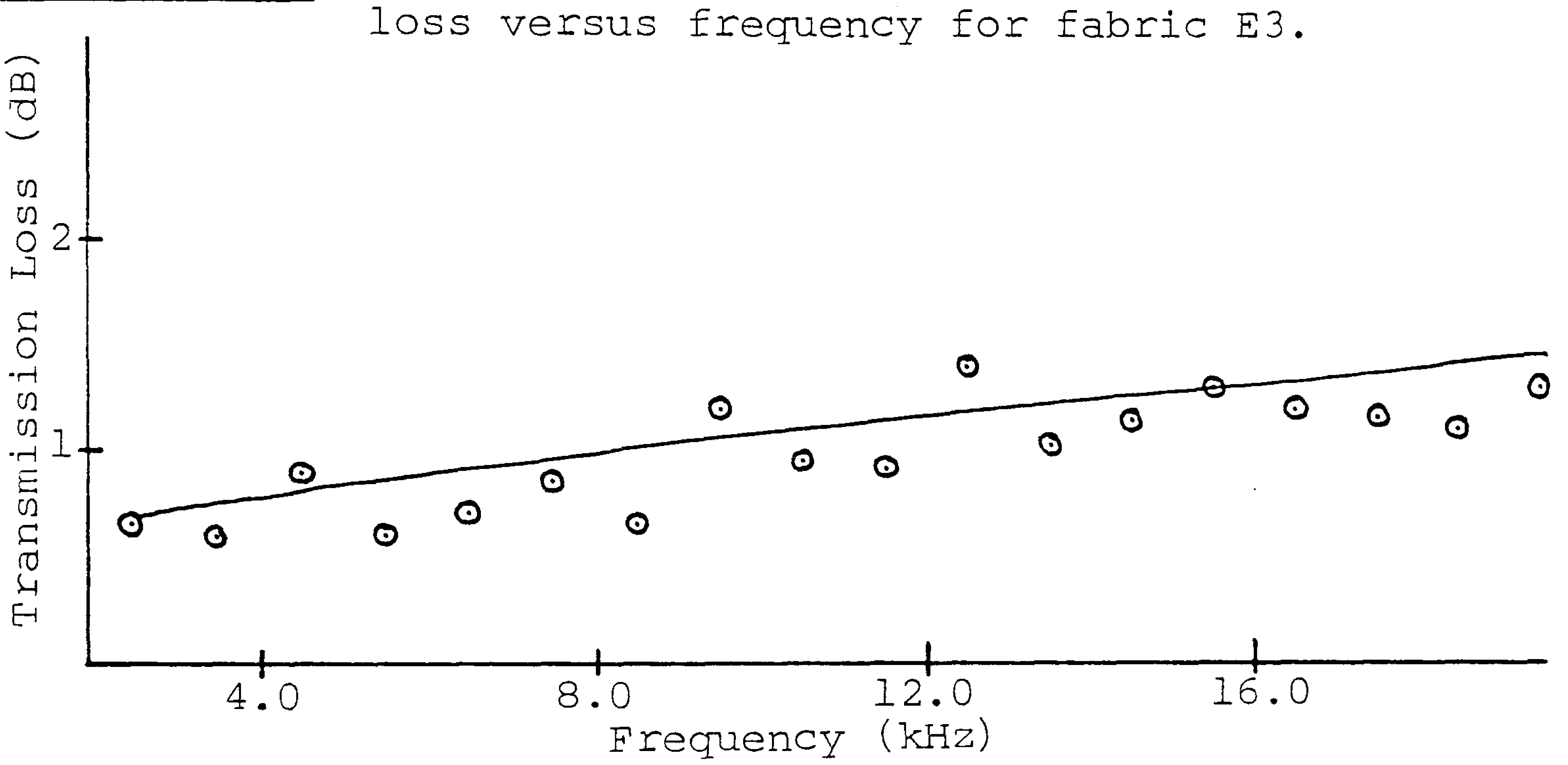


Figure A2.66 Experimental and theoretical transmission loss versus frequency for fabric E4.

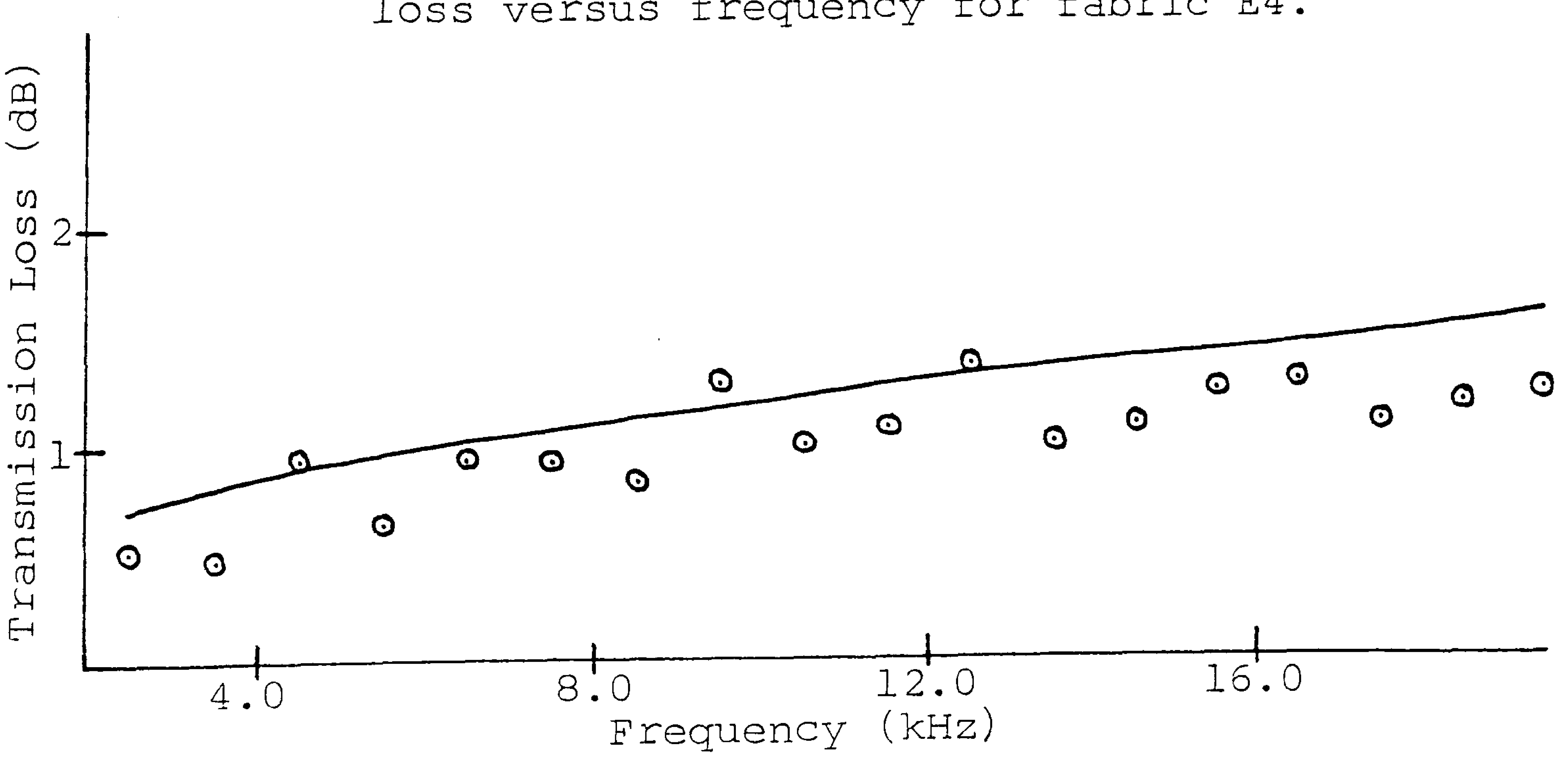


Figure A2.67 Experimental and theoretical transmission loss versus frequency for fabric E5.

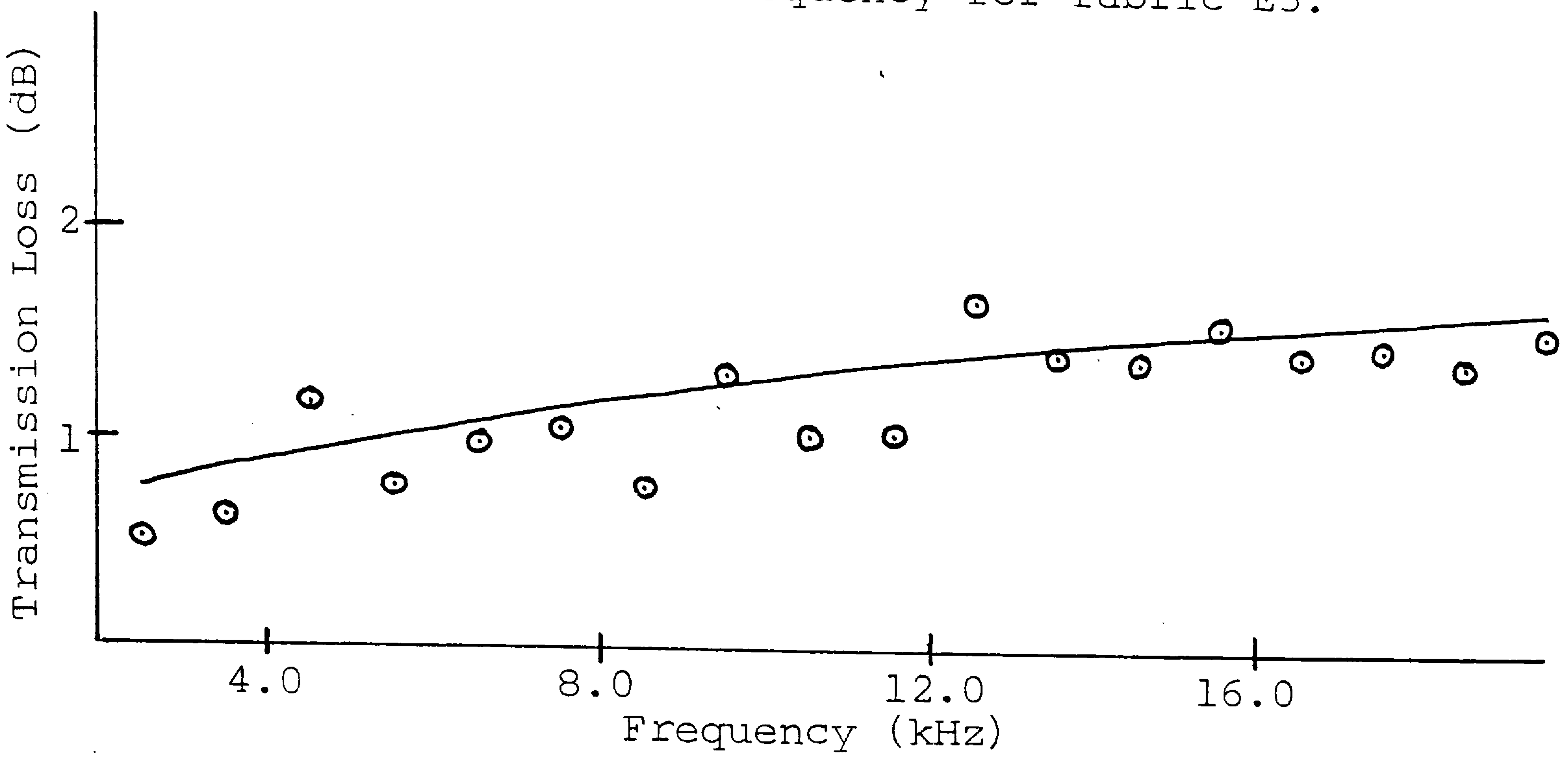


Figure A2.68 Experimental and theoretical transmission loss versus frequency for fabric E6.

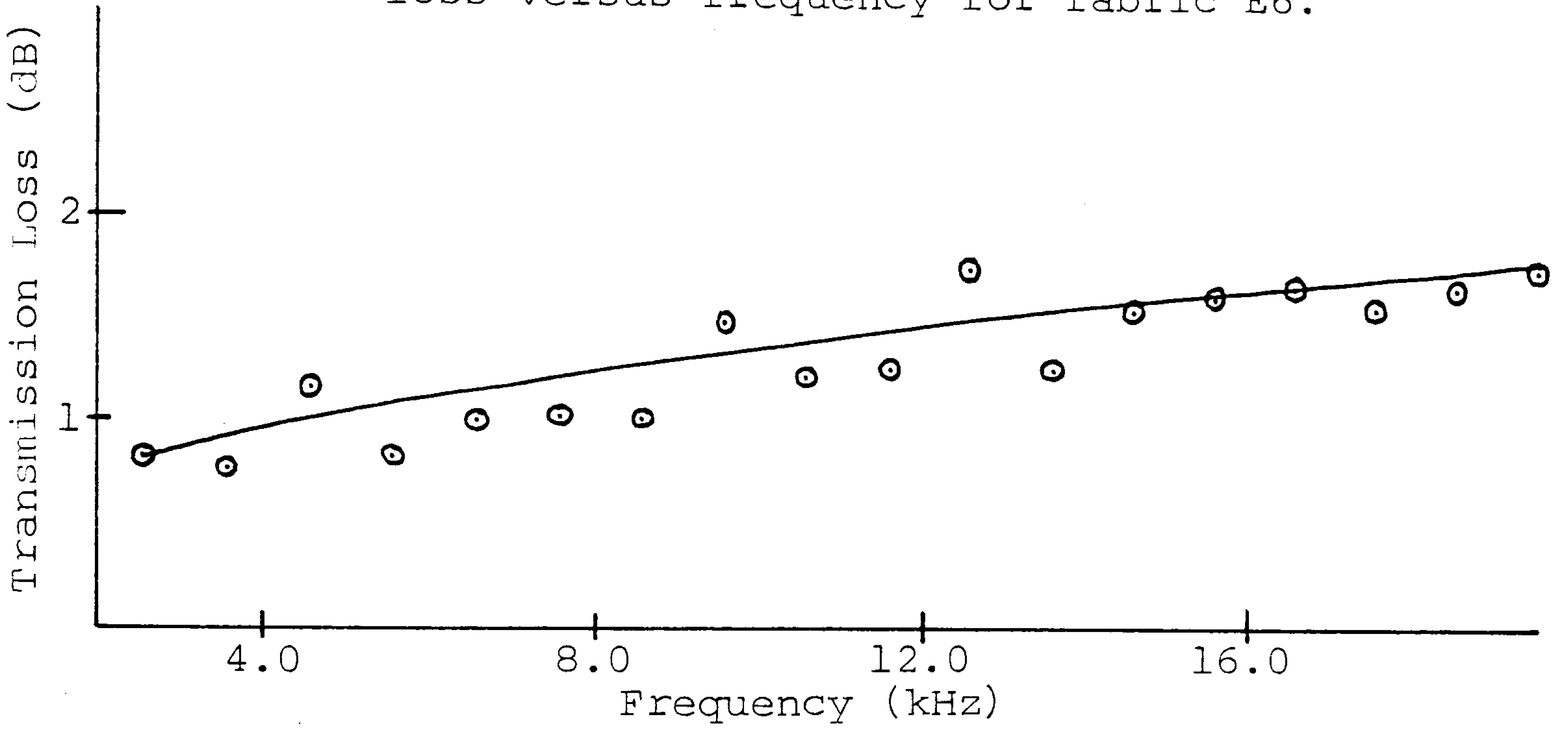


Figure A2.69 Experimental and theoretical transmission loss versus frequency for fabric E7.

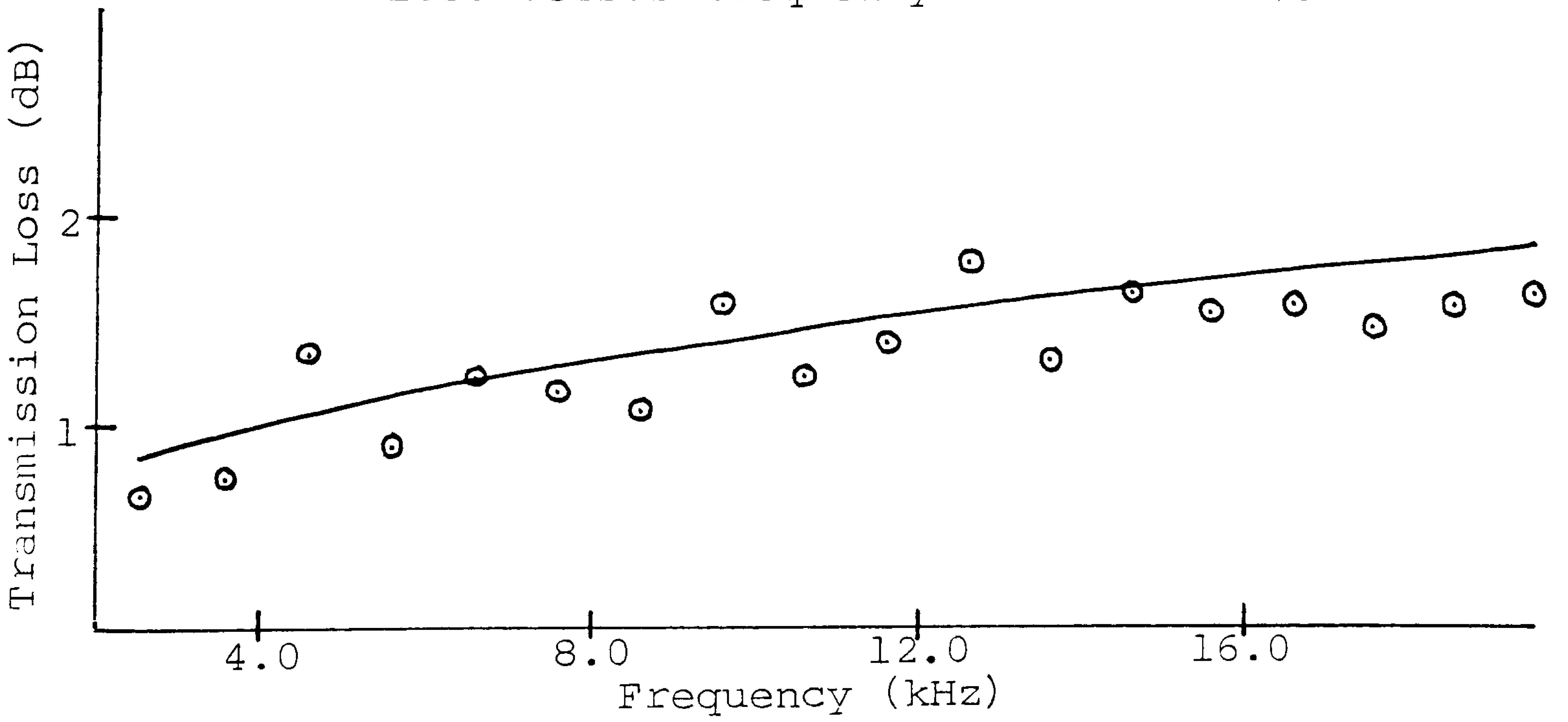


Figure A2.70 Experimental and theoretical transmission loss versus frequency for fabric E8.

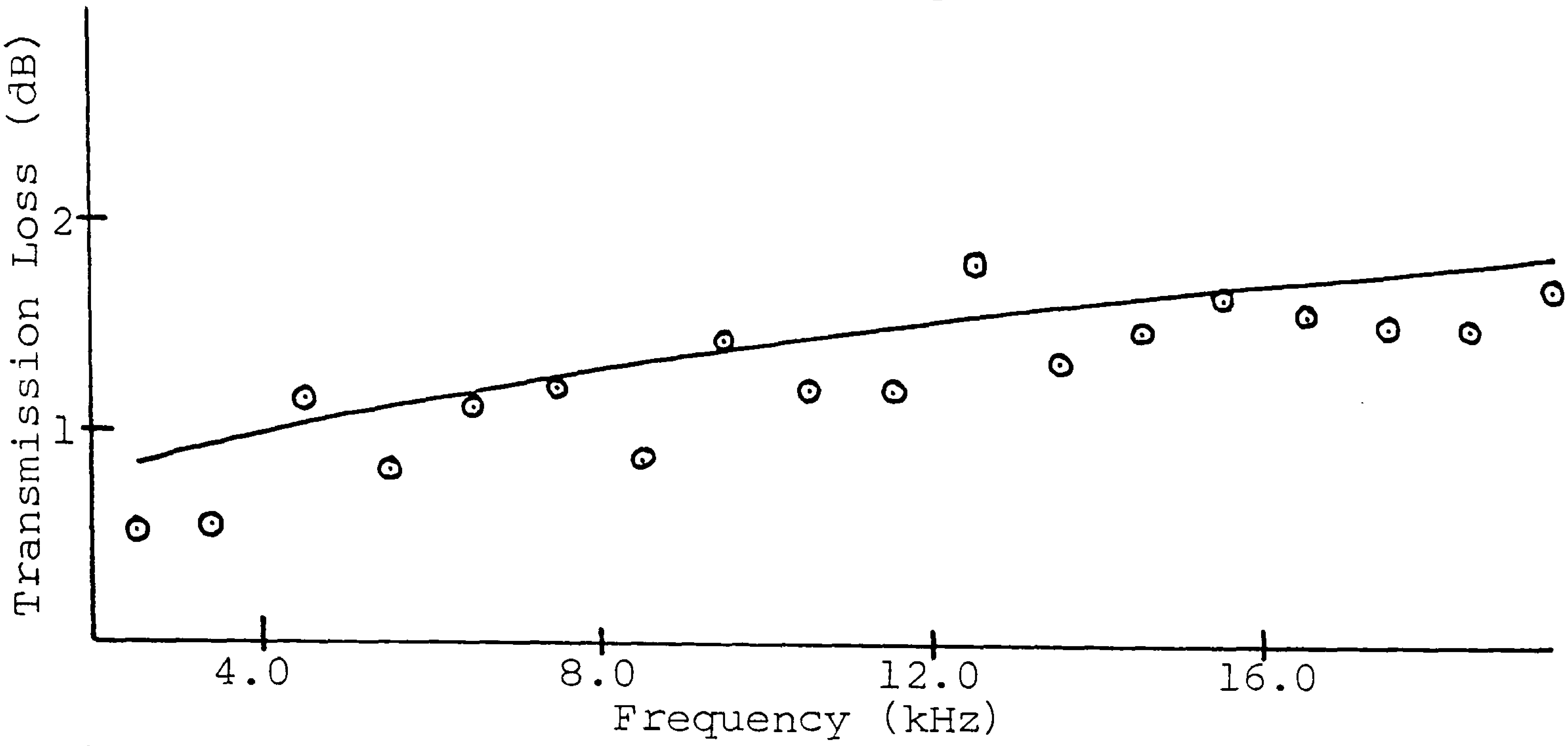


Figure A2.71 Experimental and theoretical transmission loss versus frequency for fabric E9.

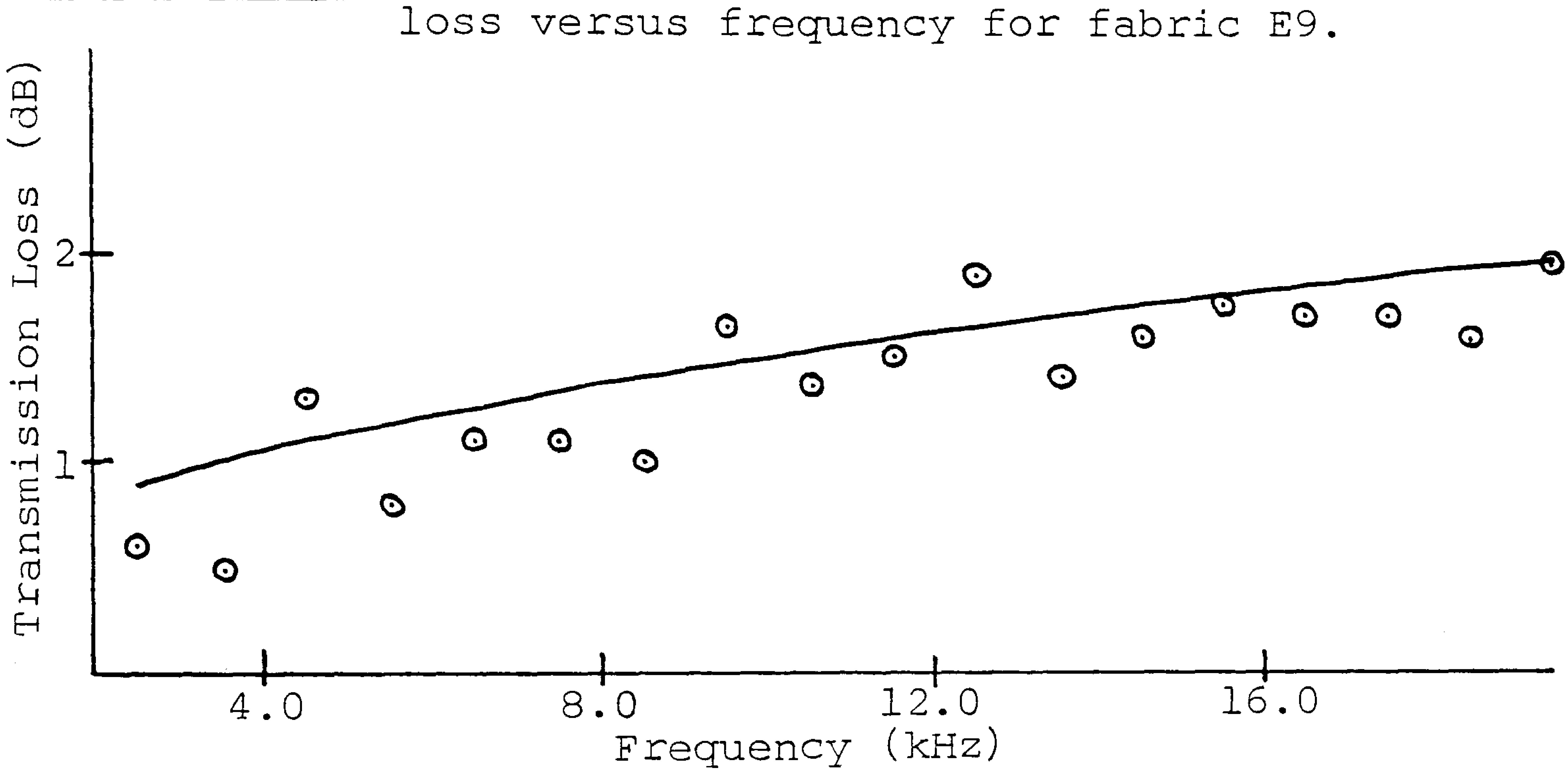


Figure A2.72 Experimental and theoretical transmission loss versus frequency for fabric E10.

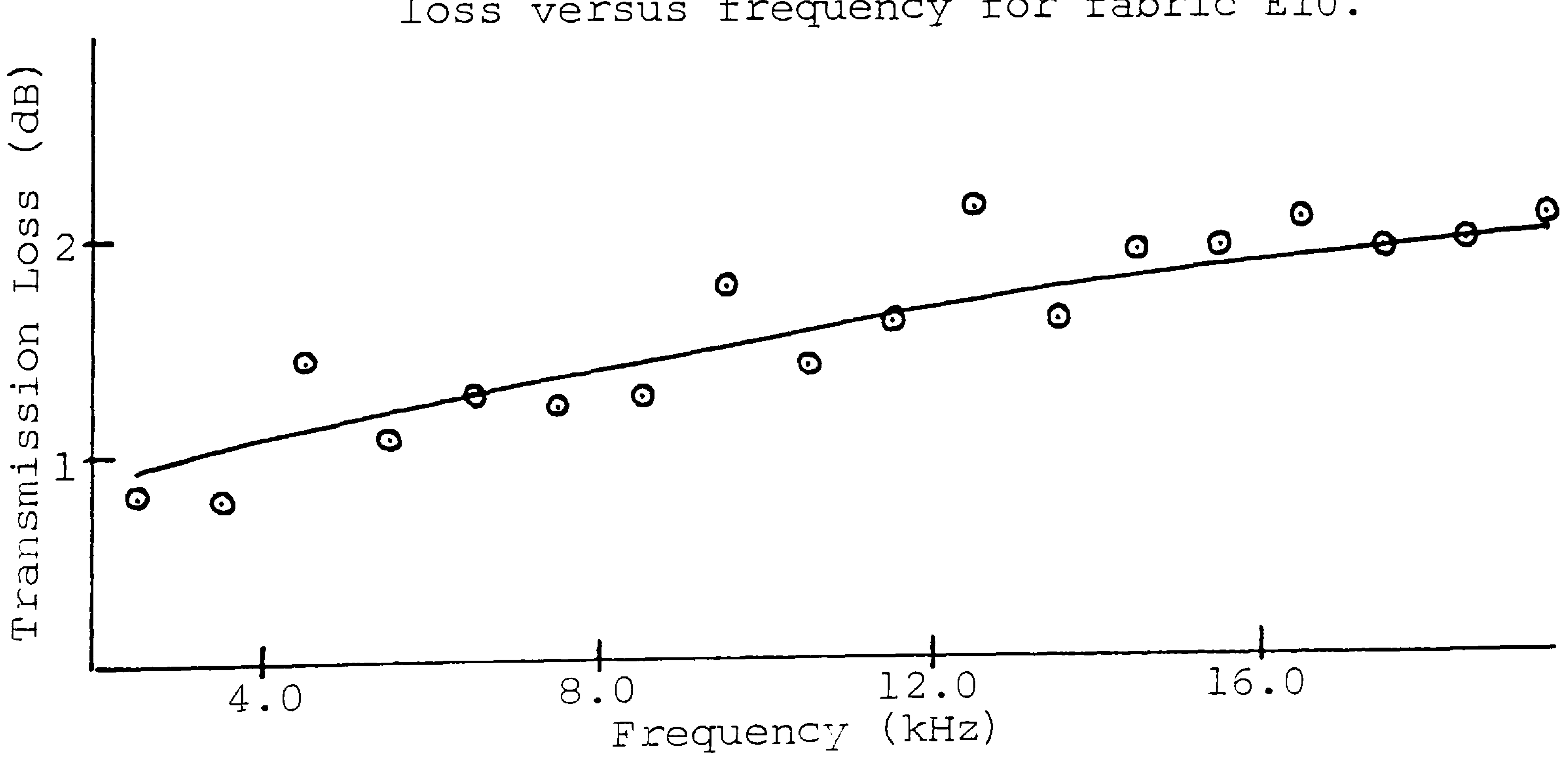


Figure A2.73 Experimental and theoretical transmission loss versus frequency for fabric E11.

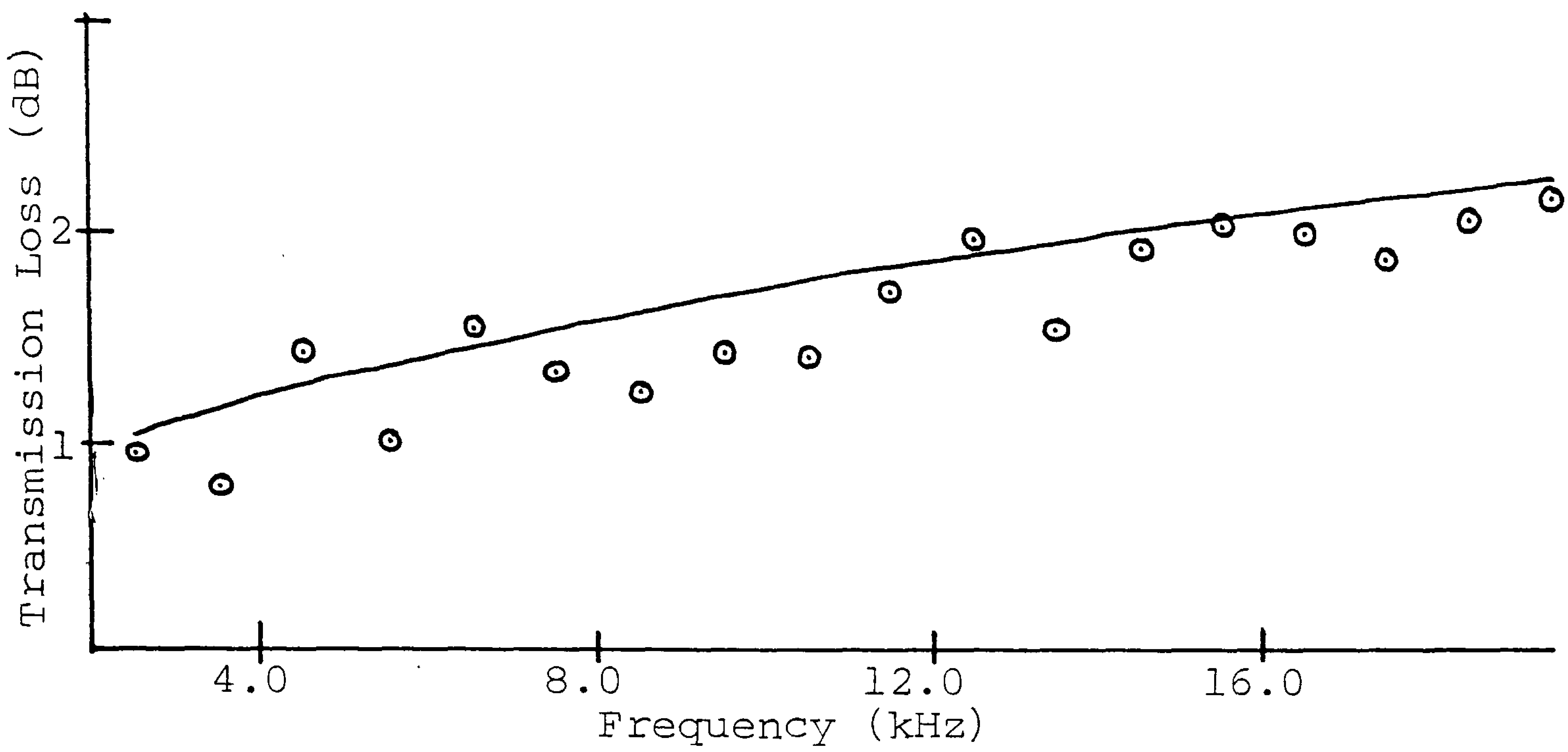


Figure A2.74 Experimental and theoretical transmission loss versus frequency for fabric E12.

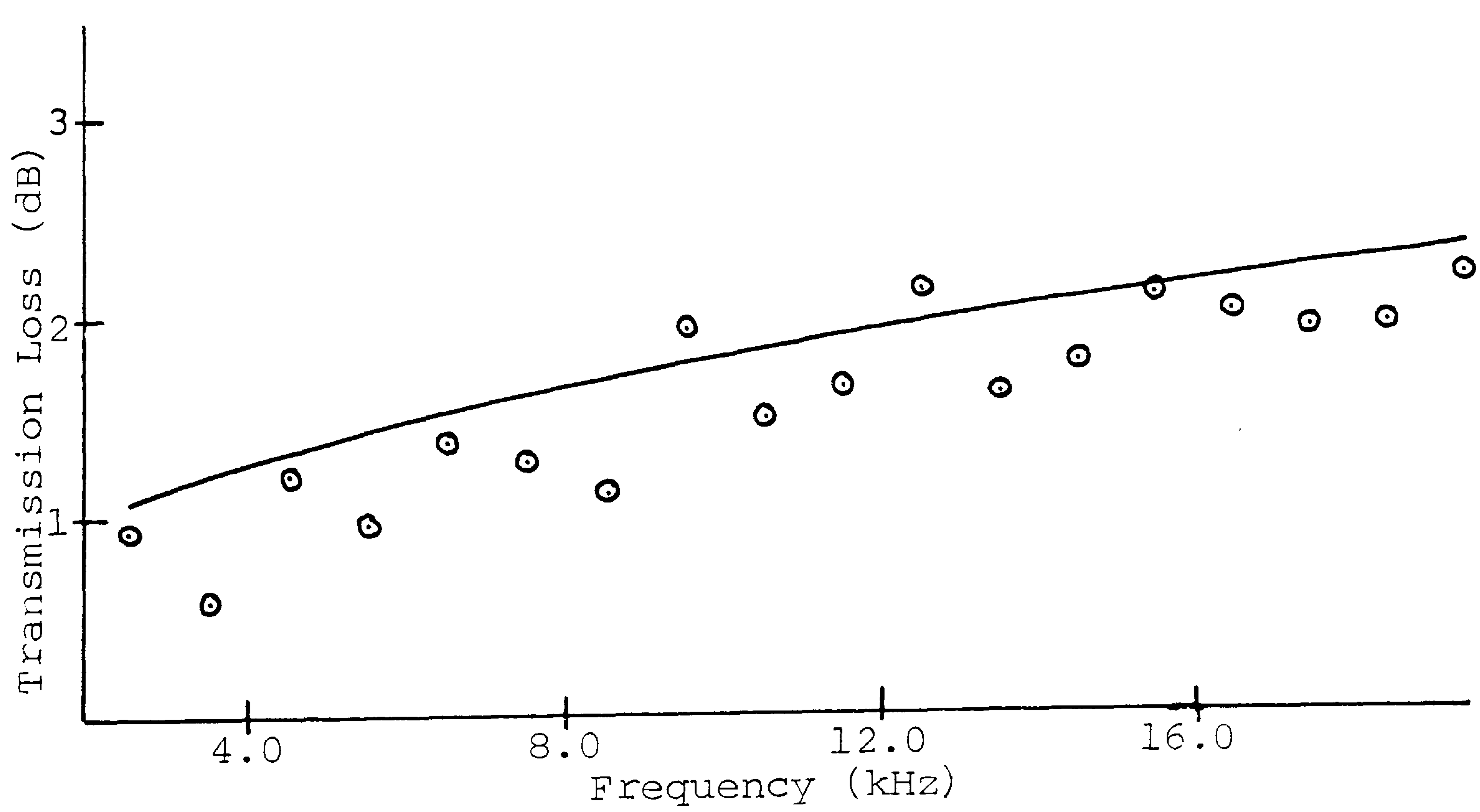


Figure A2.75 Experimental and theoretical transmission loss versus frequency for fabric F1.

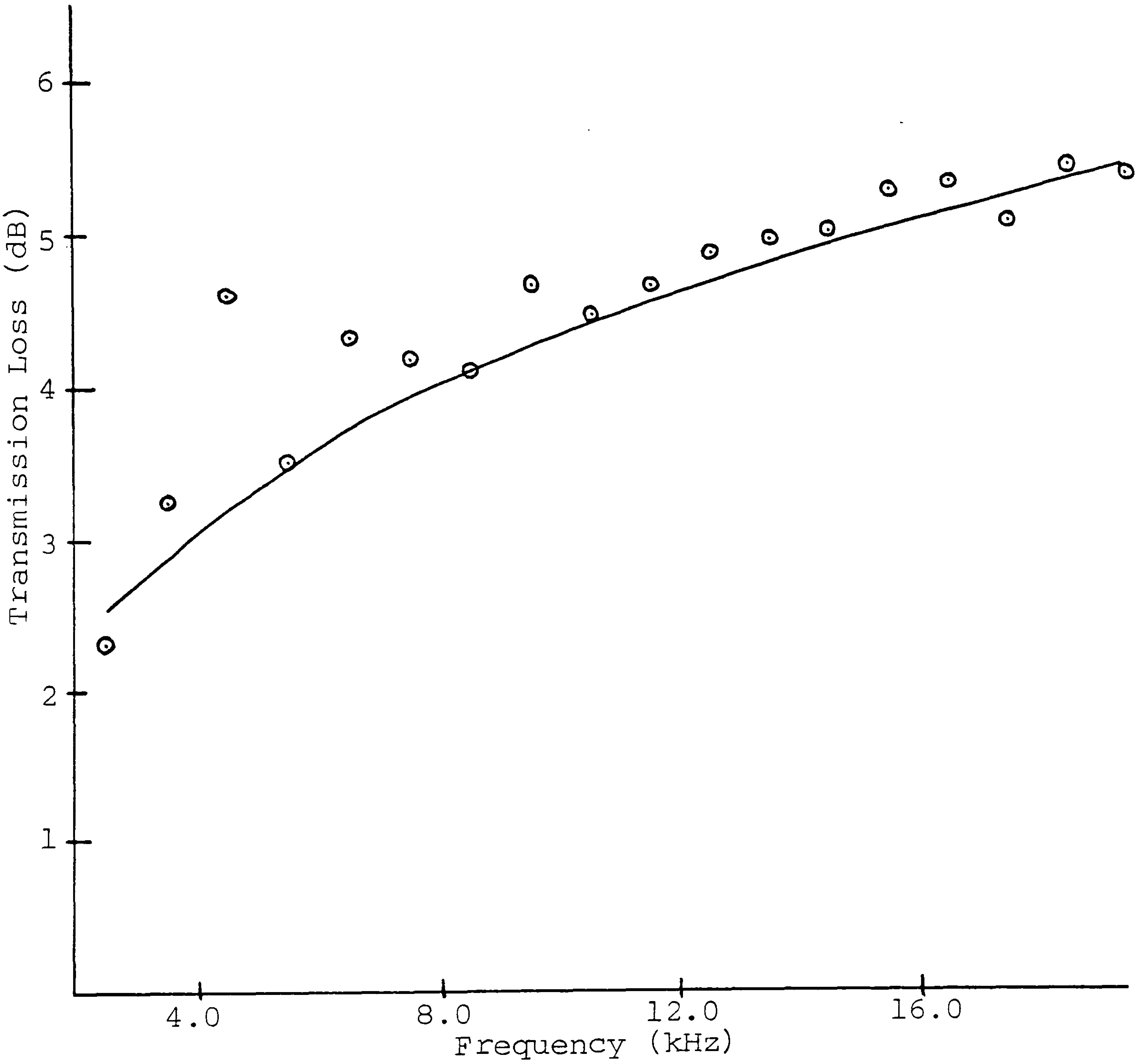


Figure A2.76 Experimental and theoretical transmission loss versus frequency for fabric F2.

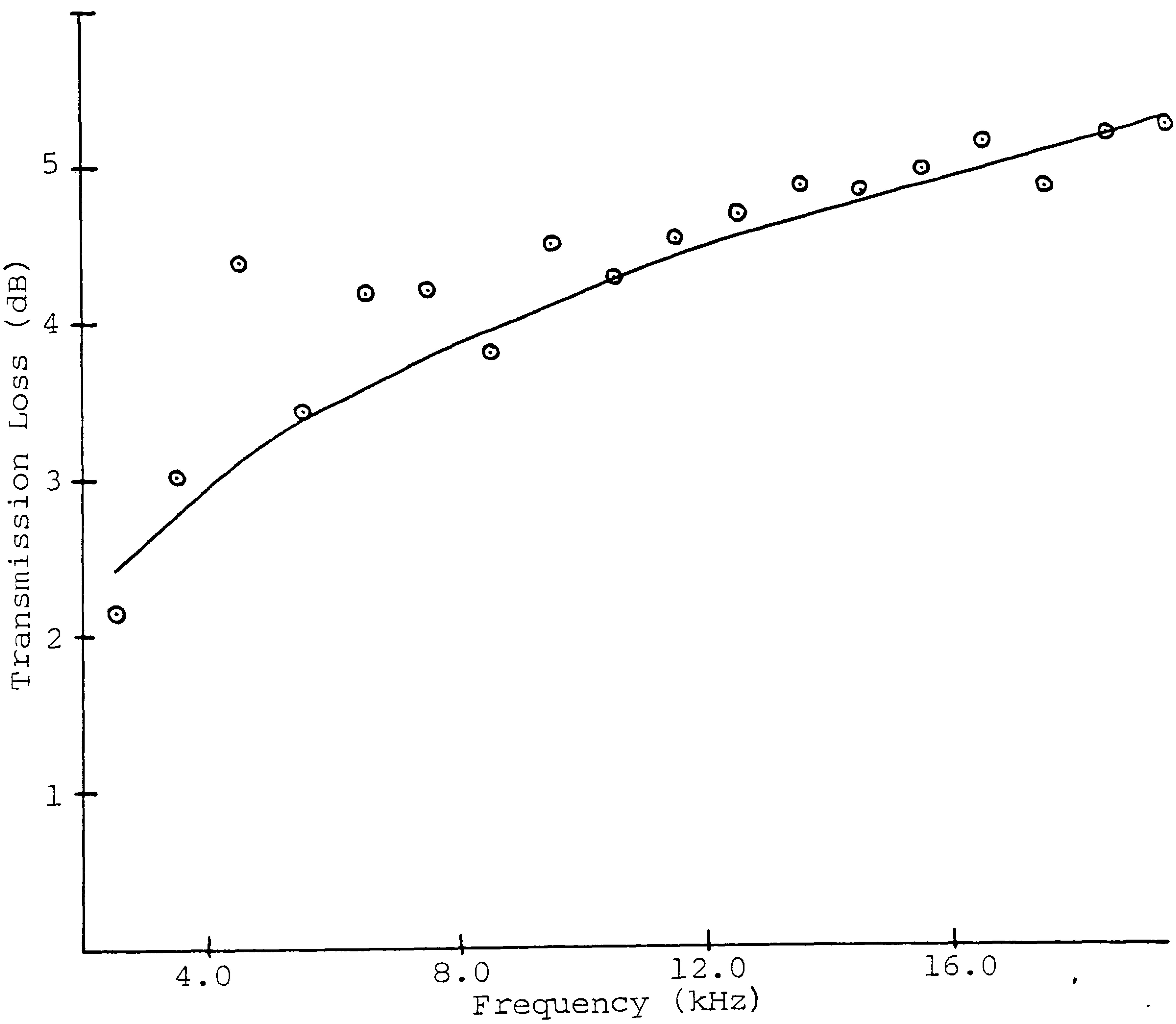


Figure A2.77 Experimental and theoretical transmission loss versus frequency for fabric F3.

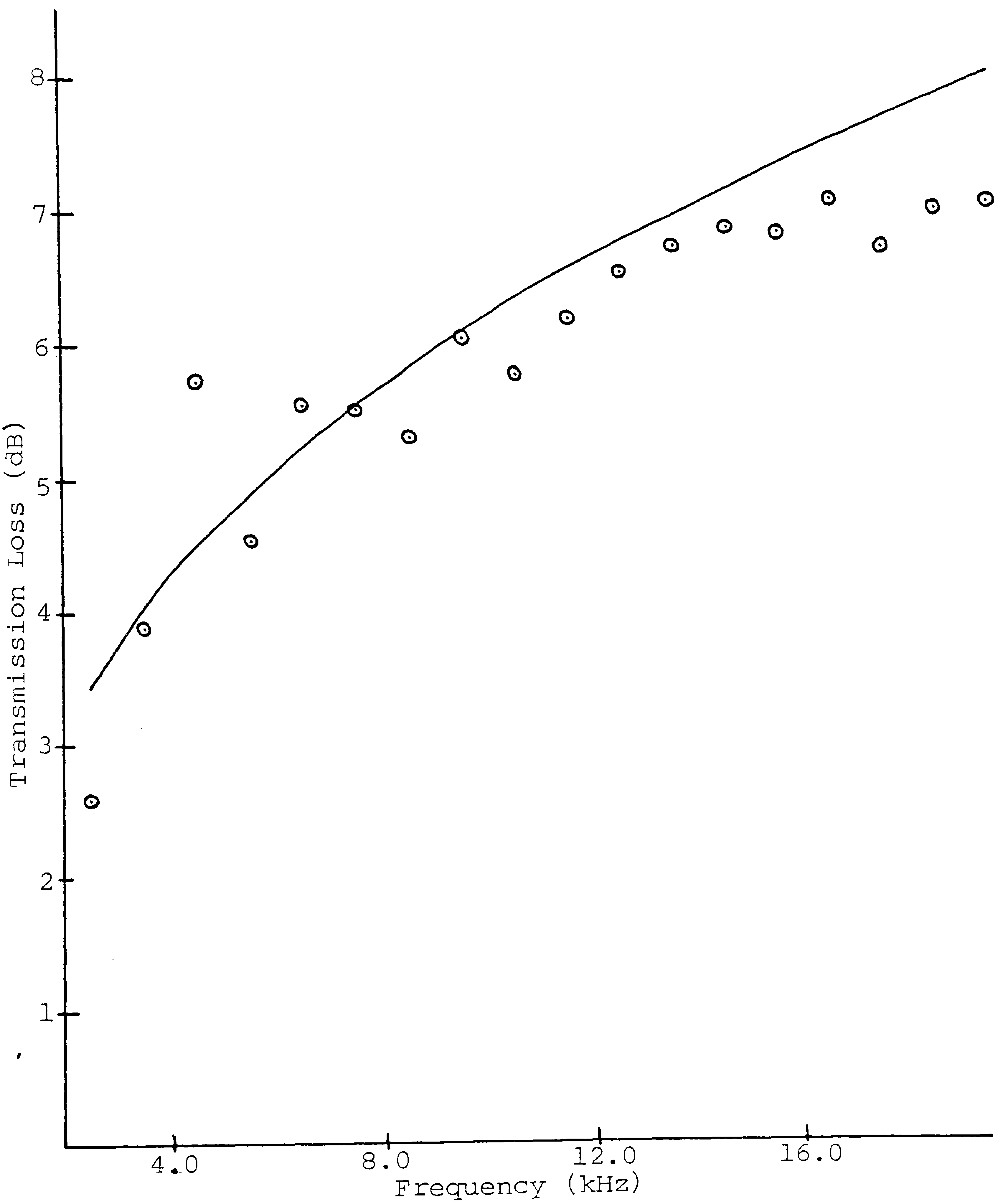


Figure A2.78 Experimental and theoretical Transmission loss versus frequency for fabric F4.

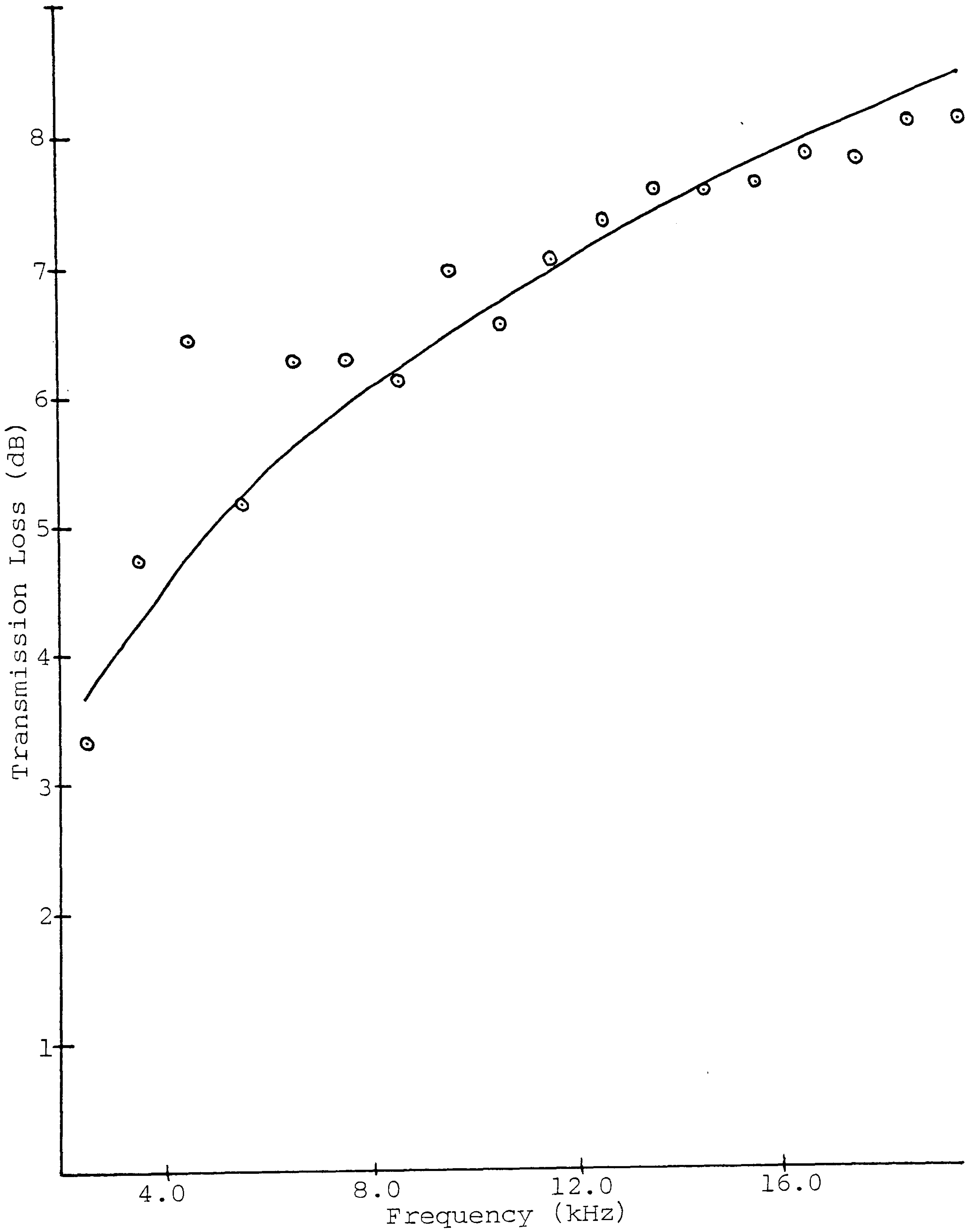


Figure A2.79 Experimental and theoretical transmission loss versus frequency for fabric F5.

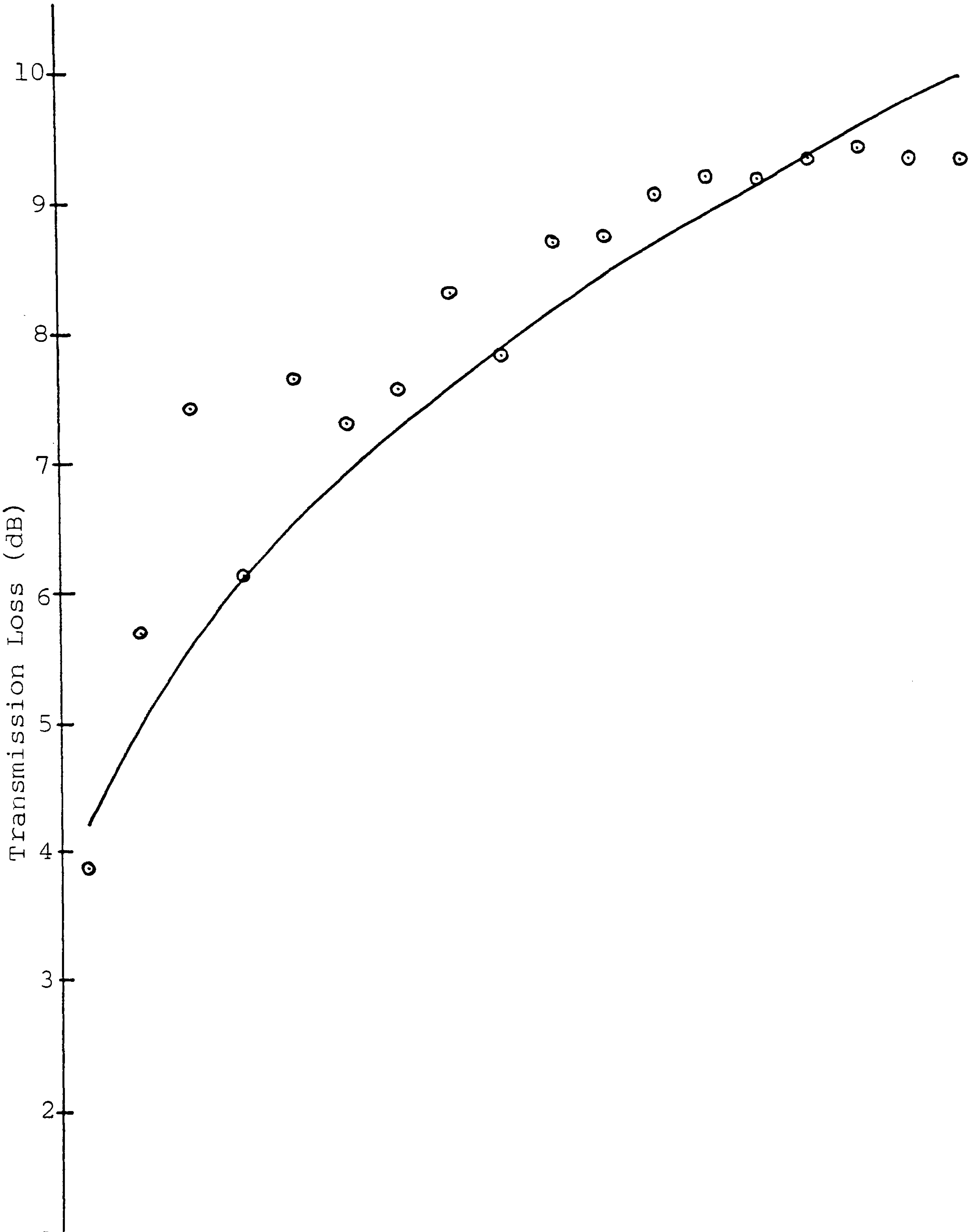


Figure A2.80 Experimental and theoretical transmission loss versus frequency for fabric F6.

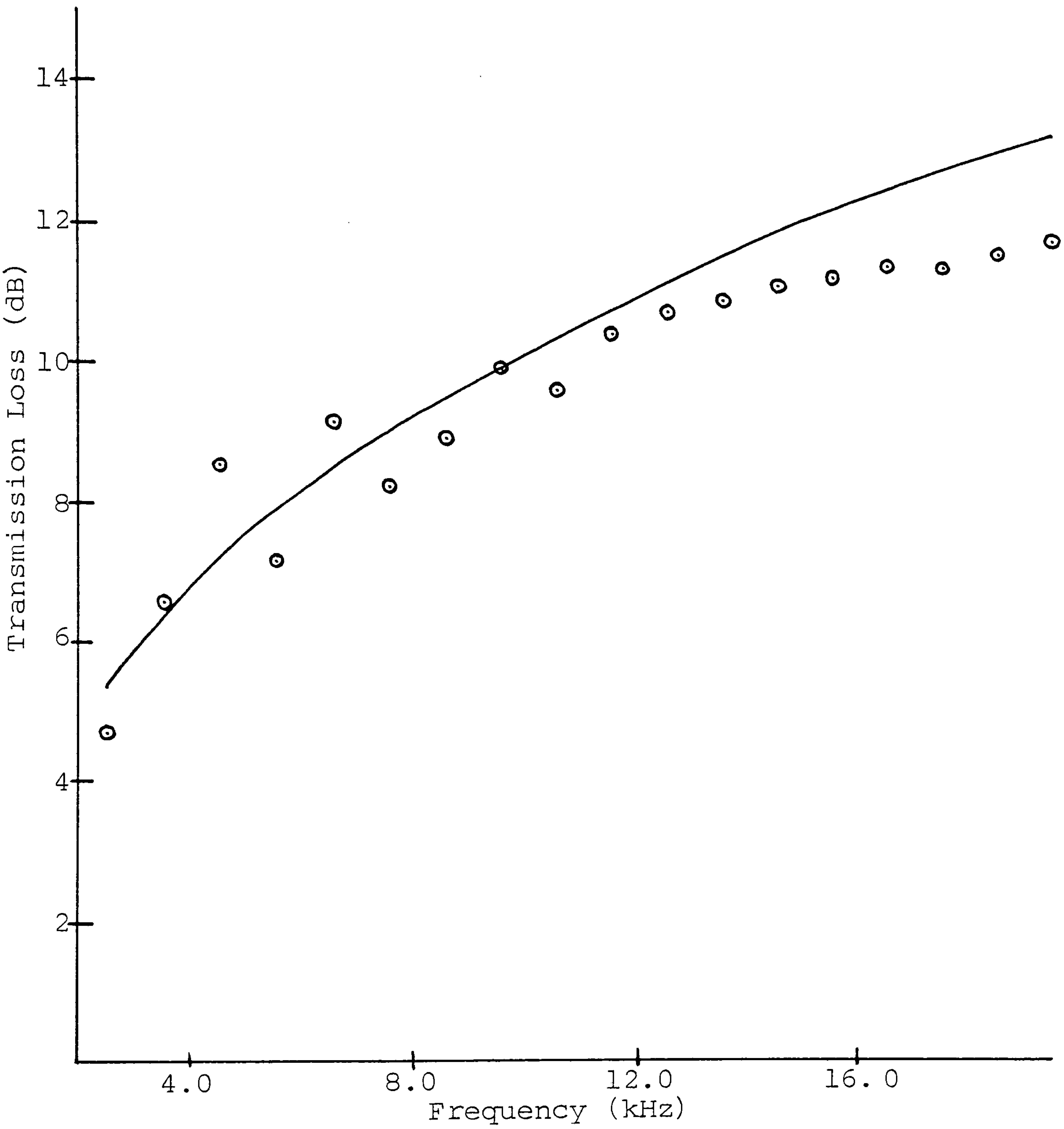


Figure A2.81 Experimental and theoretical transmission loss versus frequency for fabric G1.

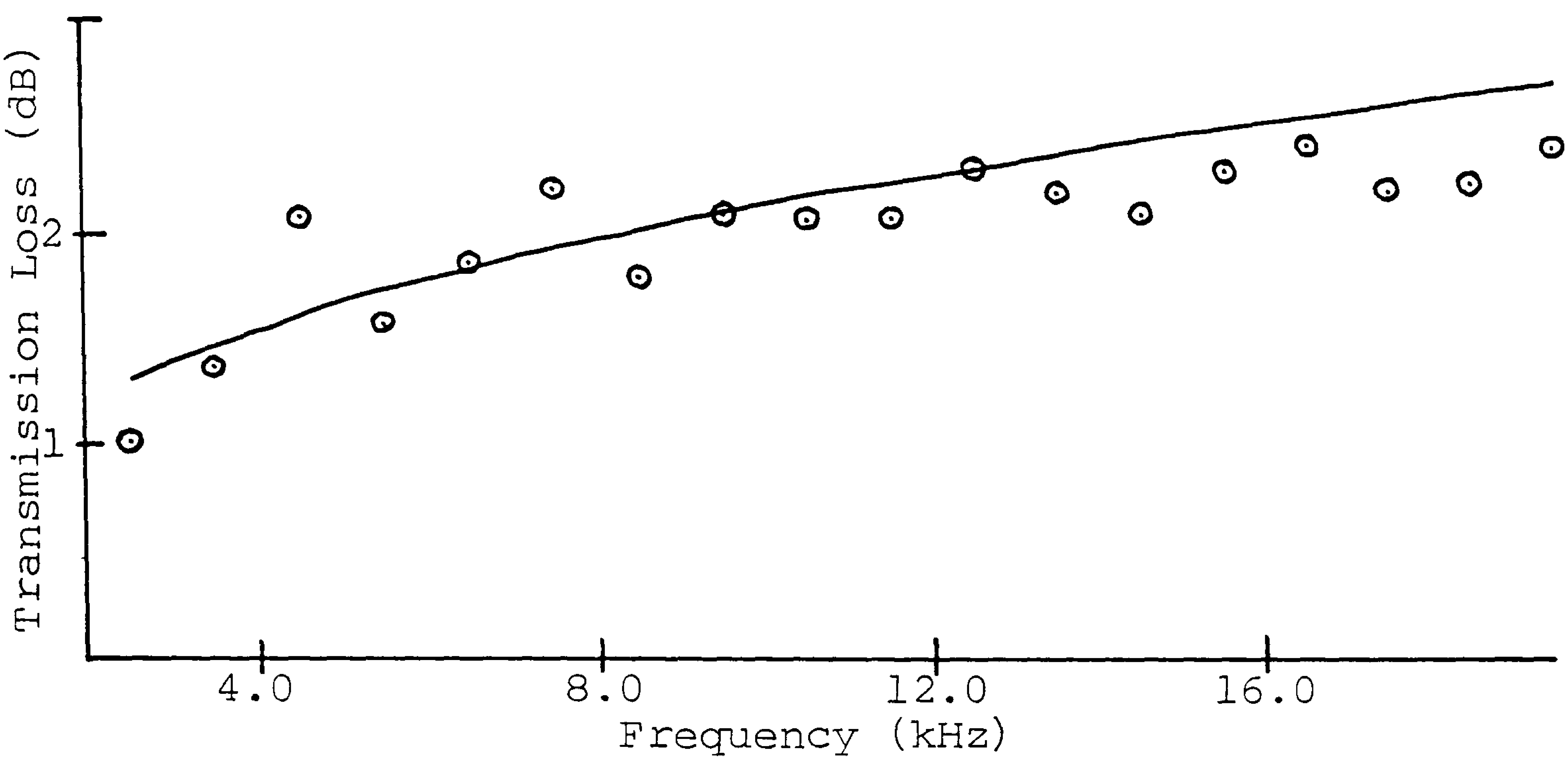


Figure A2.82 Experimental and theoretical transmission loss versus frequency for fabric G2.

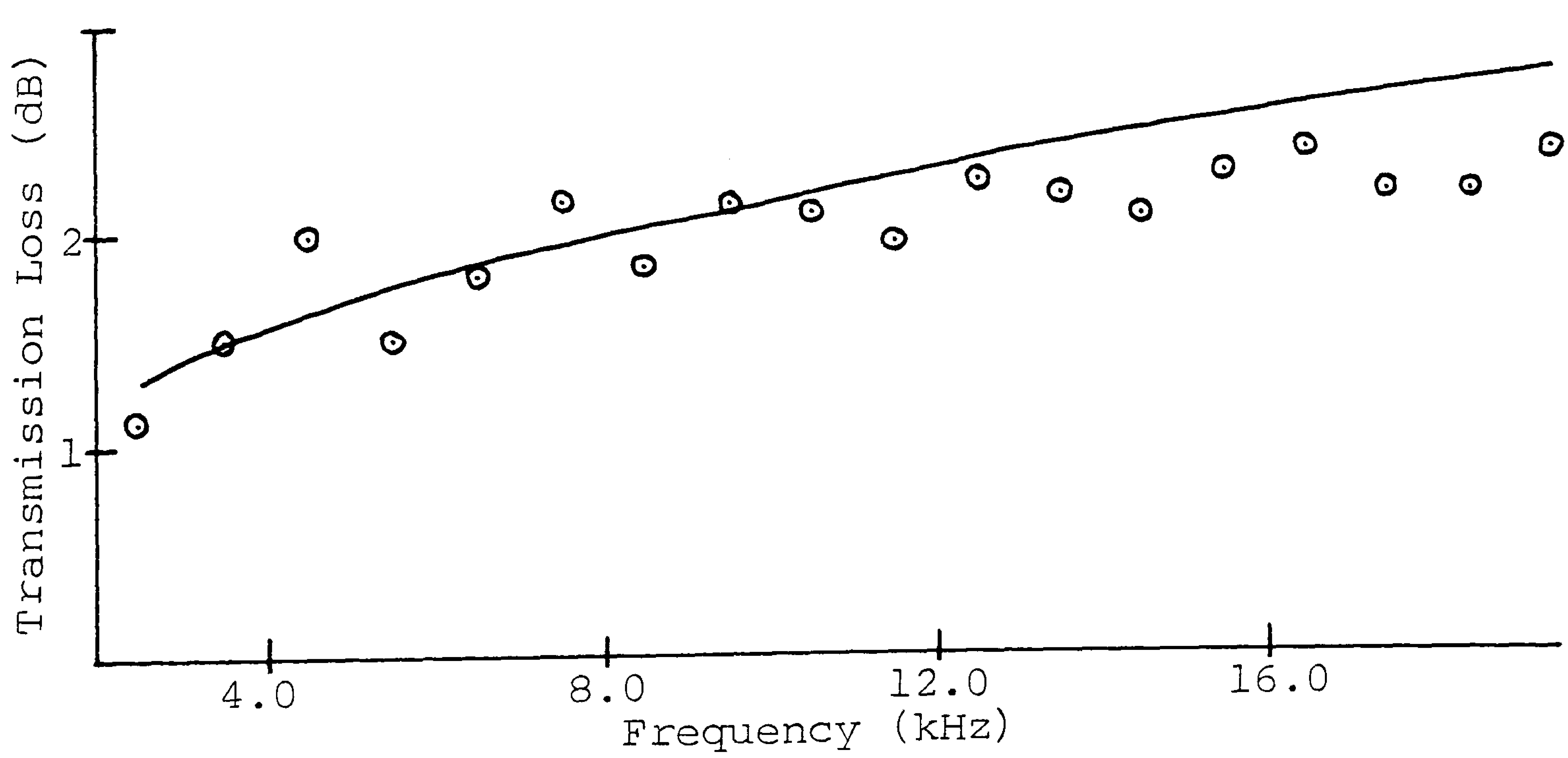


Figure A2.83 Experimental and theoretical transmission loss versus frequency for fabric G3.

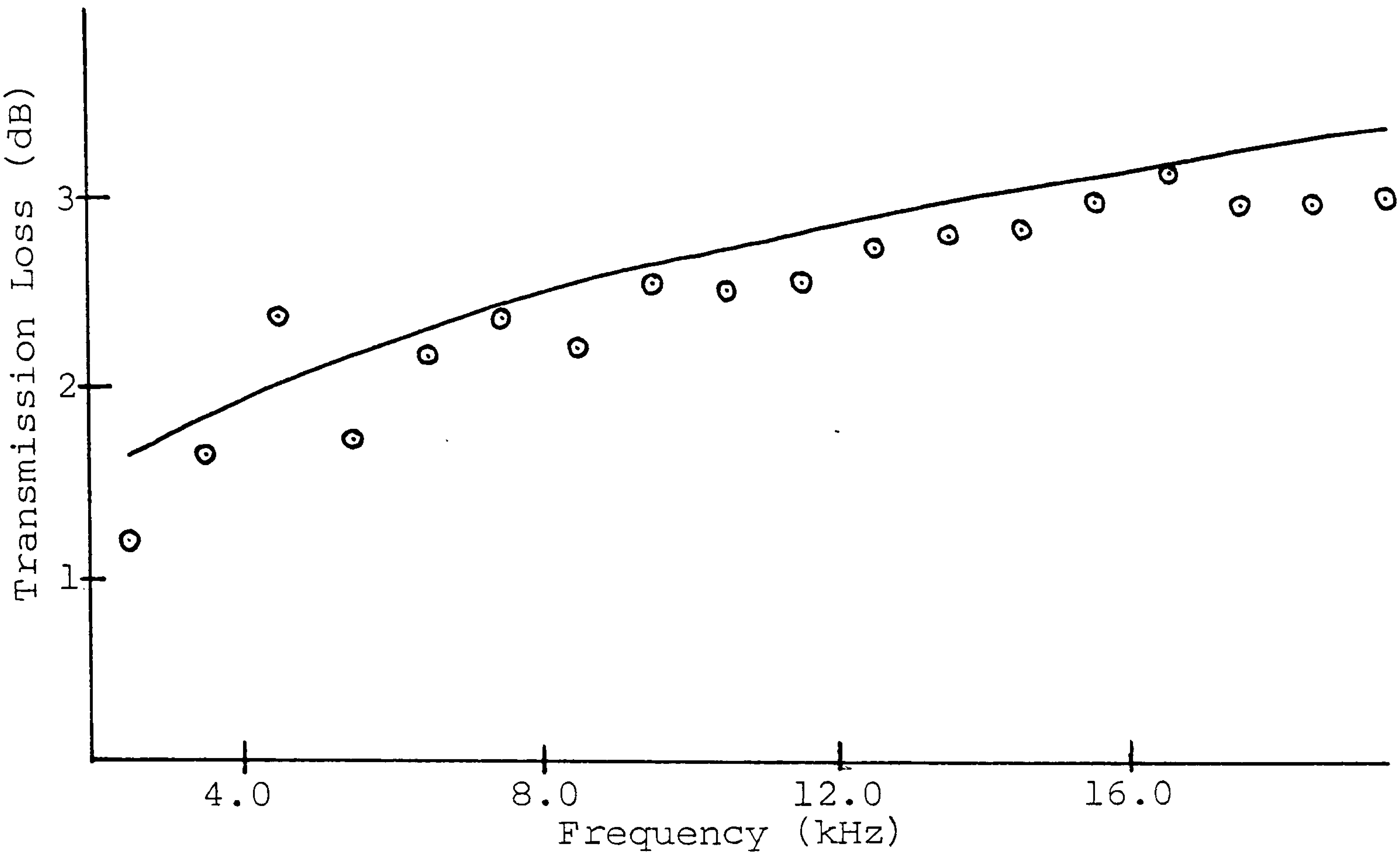


Figure A2.84 Experimental and theoretical transmission loss versus frequency for fabric G4.

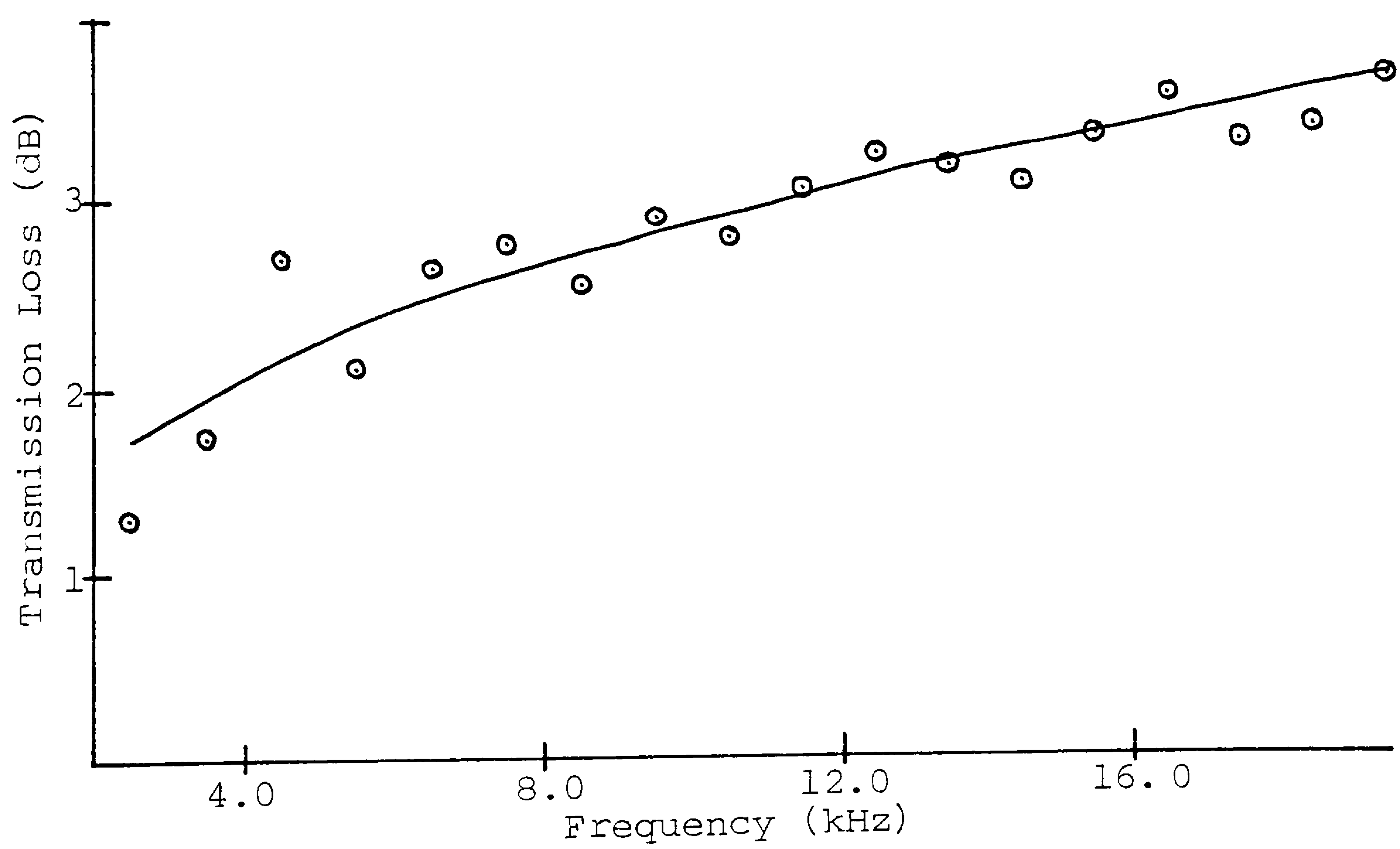


Figure A2.85 Experimental and theoretical transmission loss versus frequency for fabric G5.

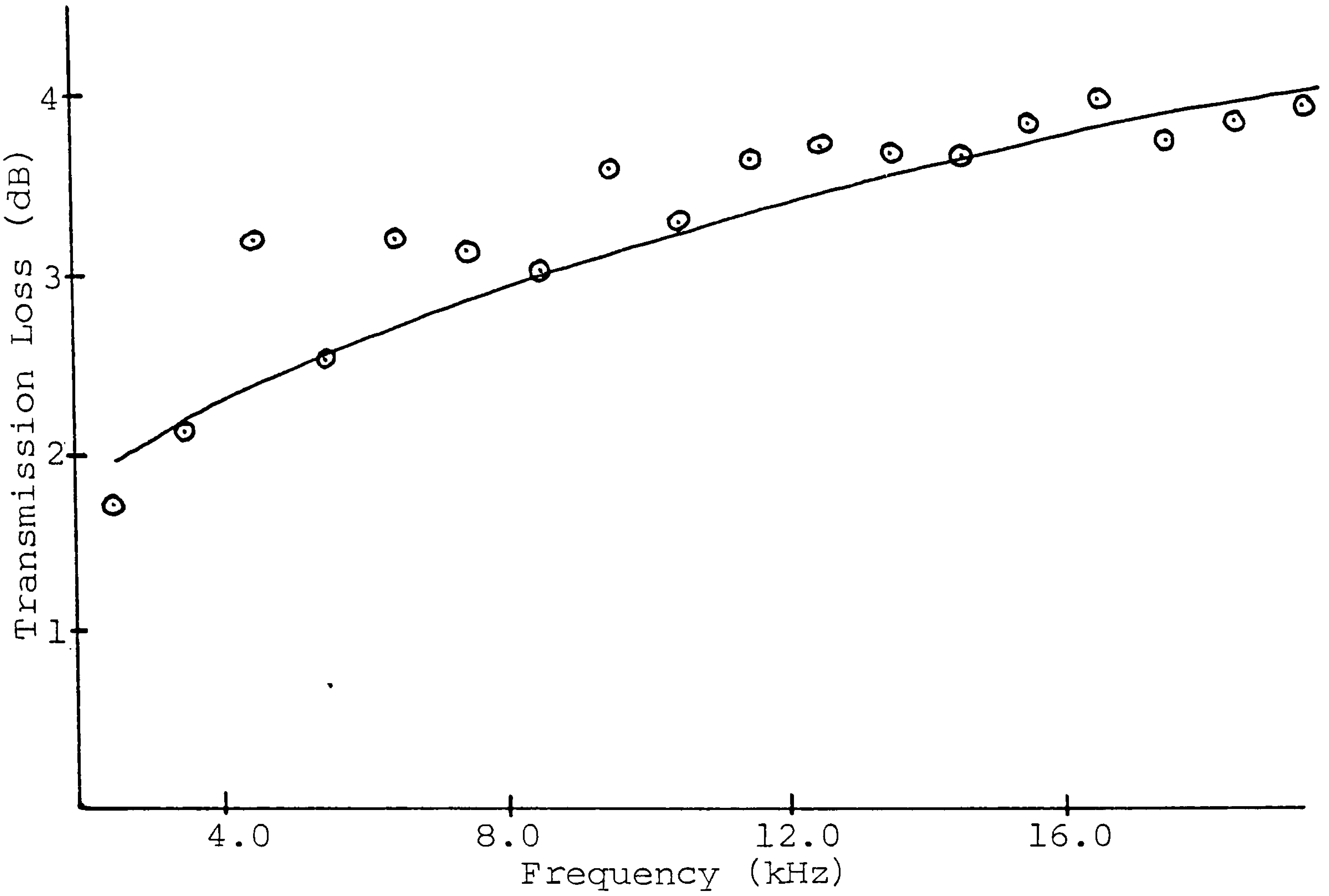


Figure A2.86 Experimental and theoretical transmission loss versus frequency for fabric G6.

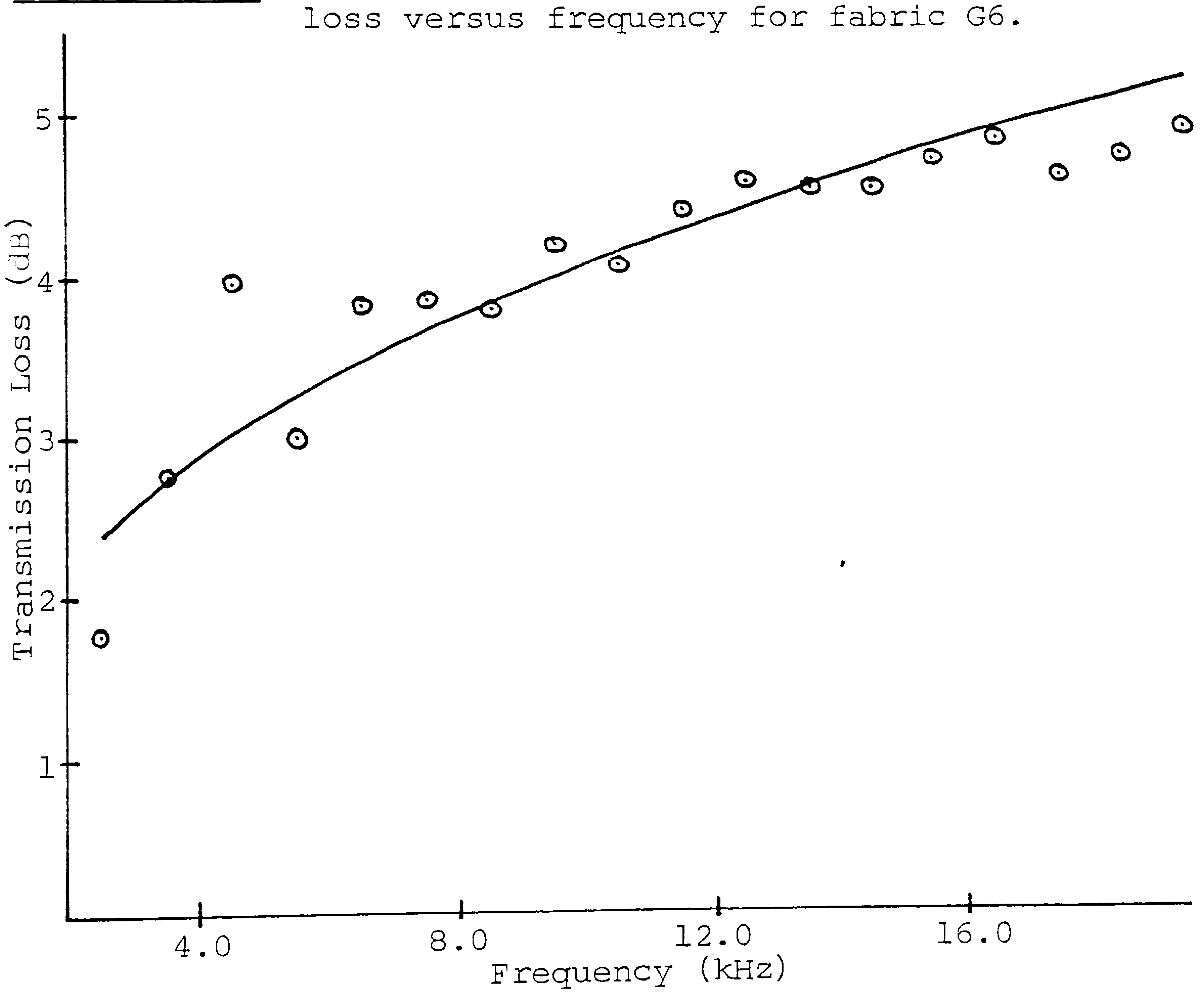


Figure A2.87 Experimental and theoretical transmission loss versus frequency for fabric G7.

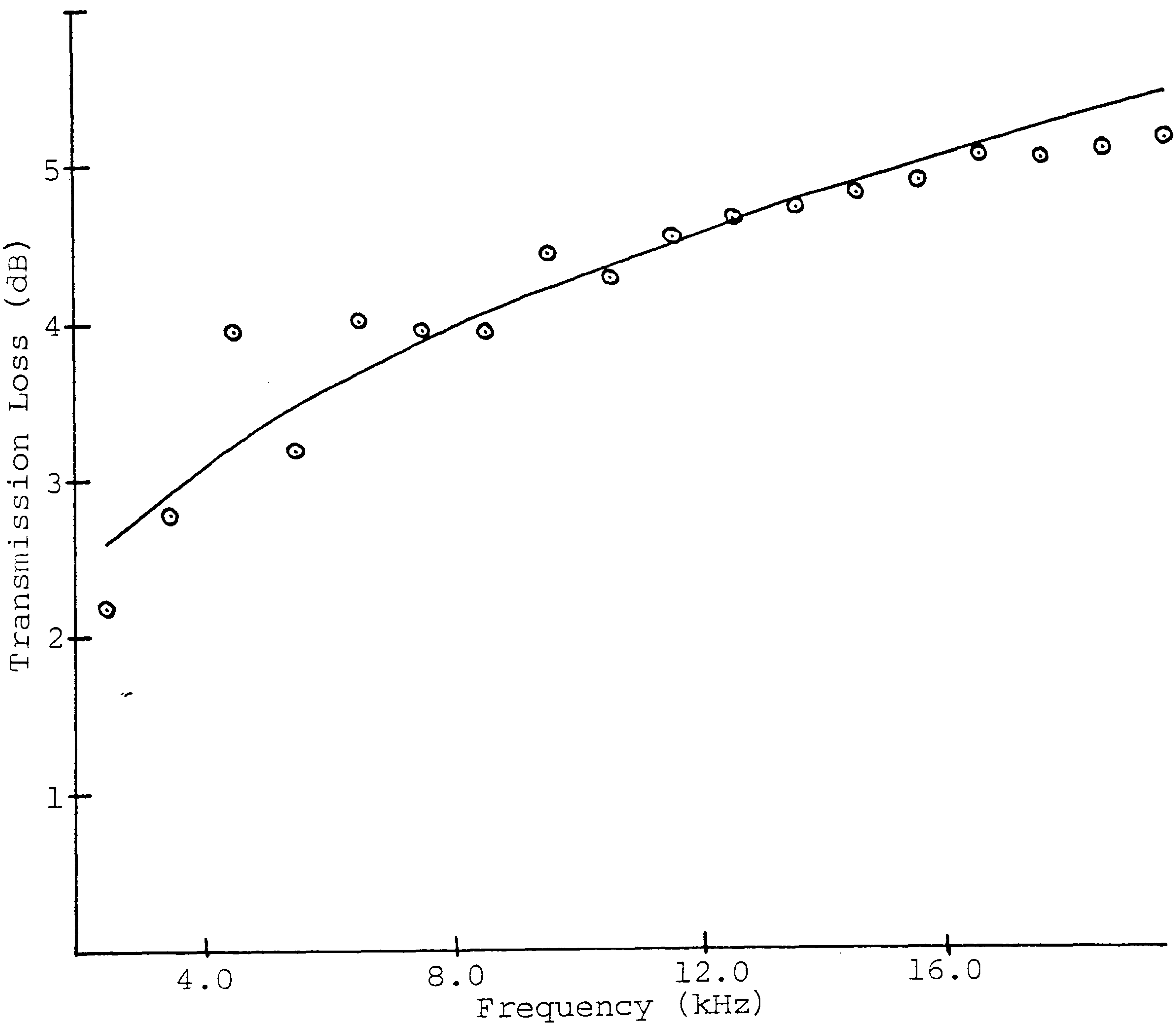


Figure A2.88 Experimental and theoretical transmission loss versus frequency for fabric G8.

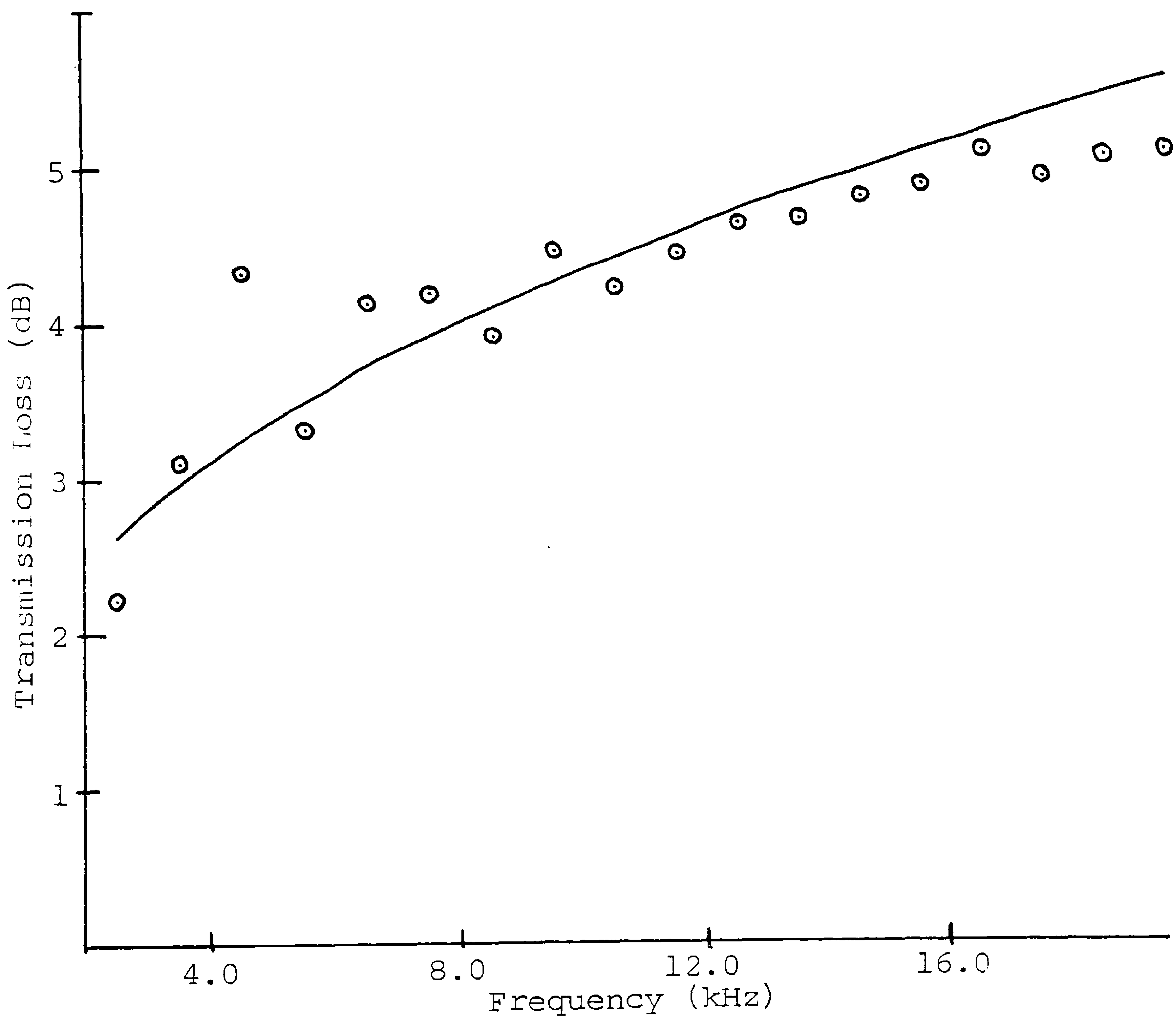


Figure A2.89 Experimental and theoretical transmission loss versus frequency for fabric G9.

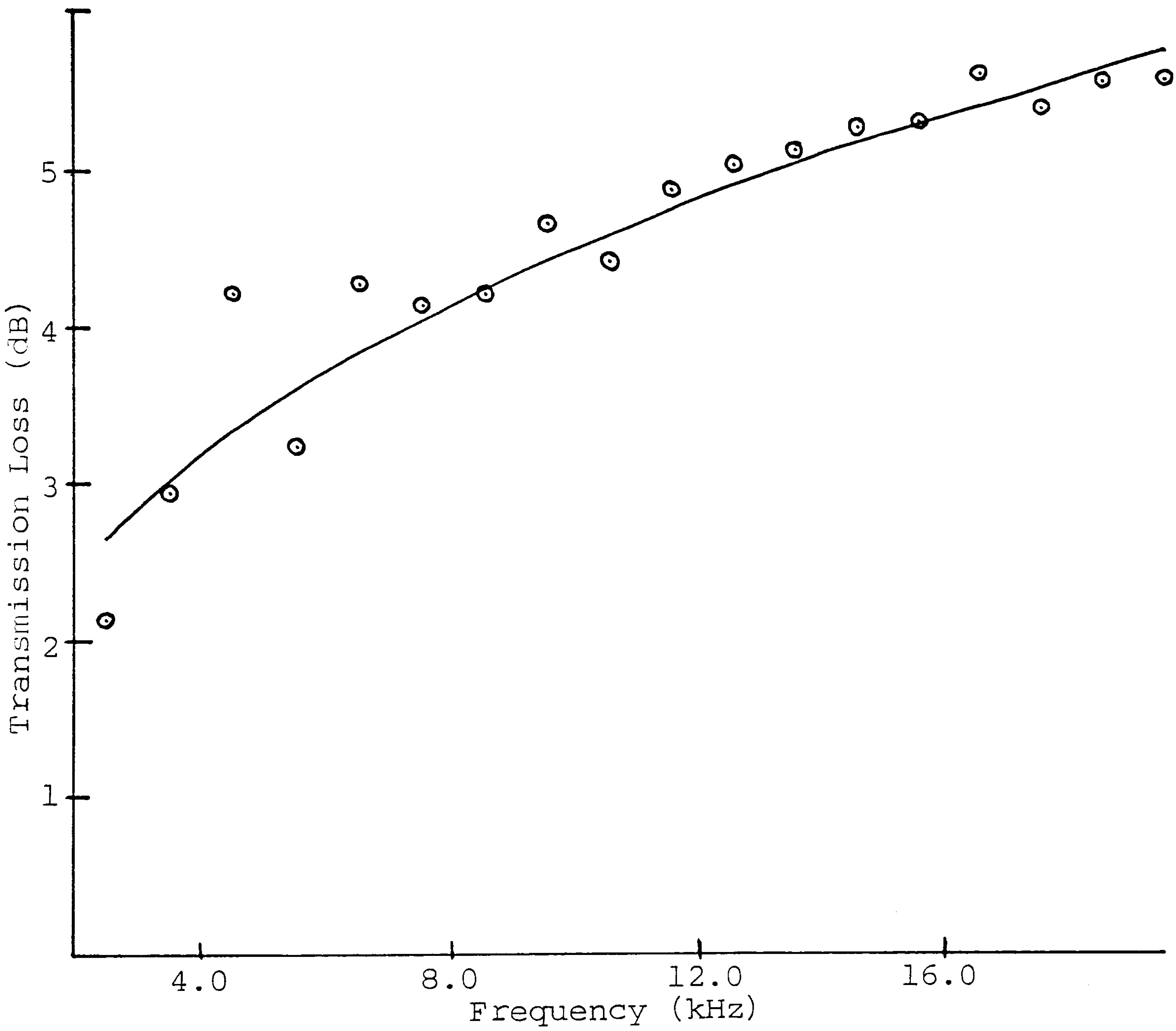


Figure A2.90 Experimental and theoretical transmission loss versus frequency for fabric G10.

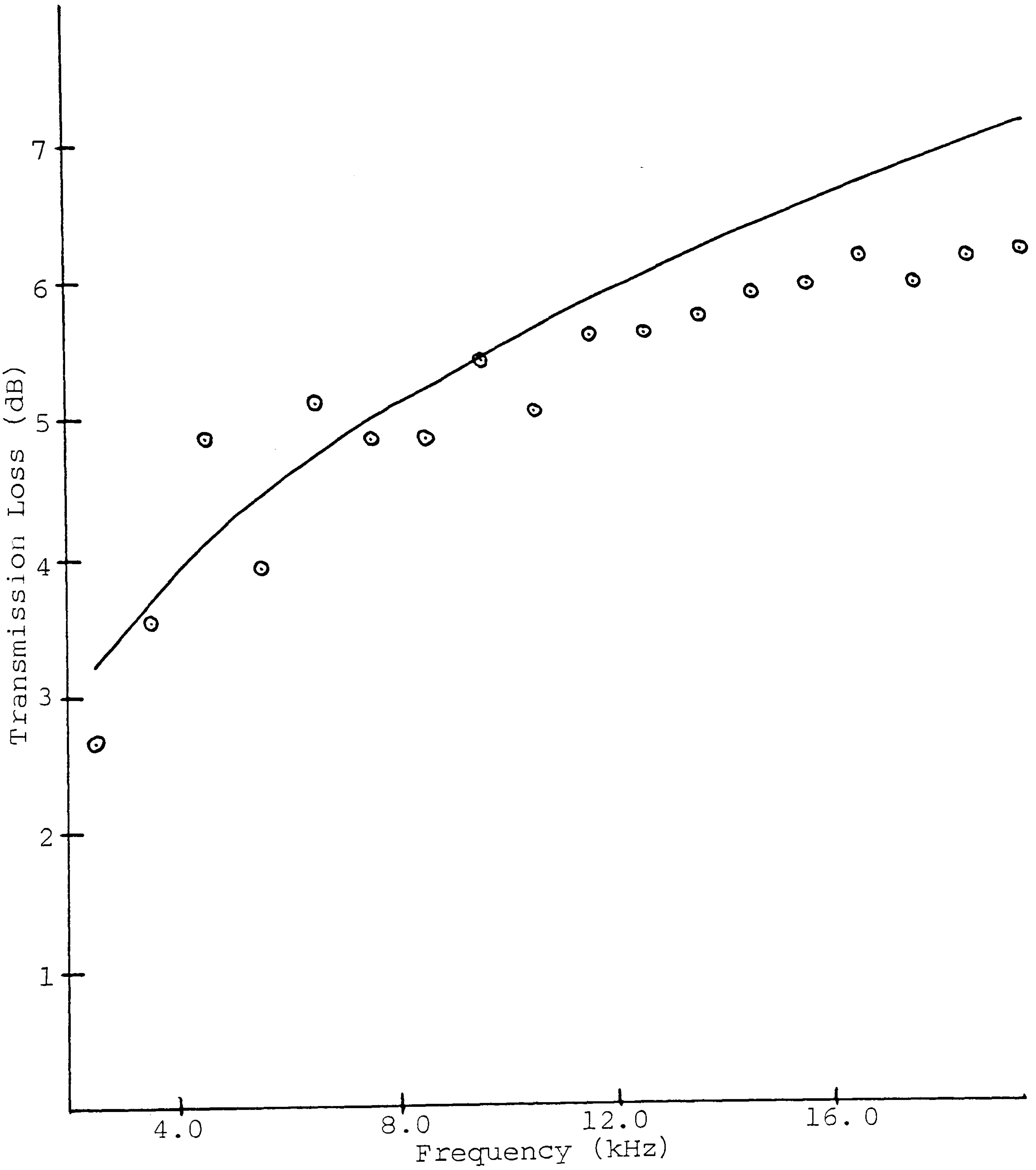


Figure A2.91 Experimental and theoretical transmission loss versus frequency for fabric G11.

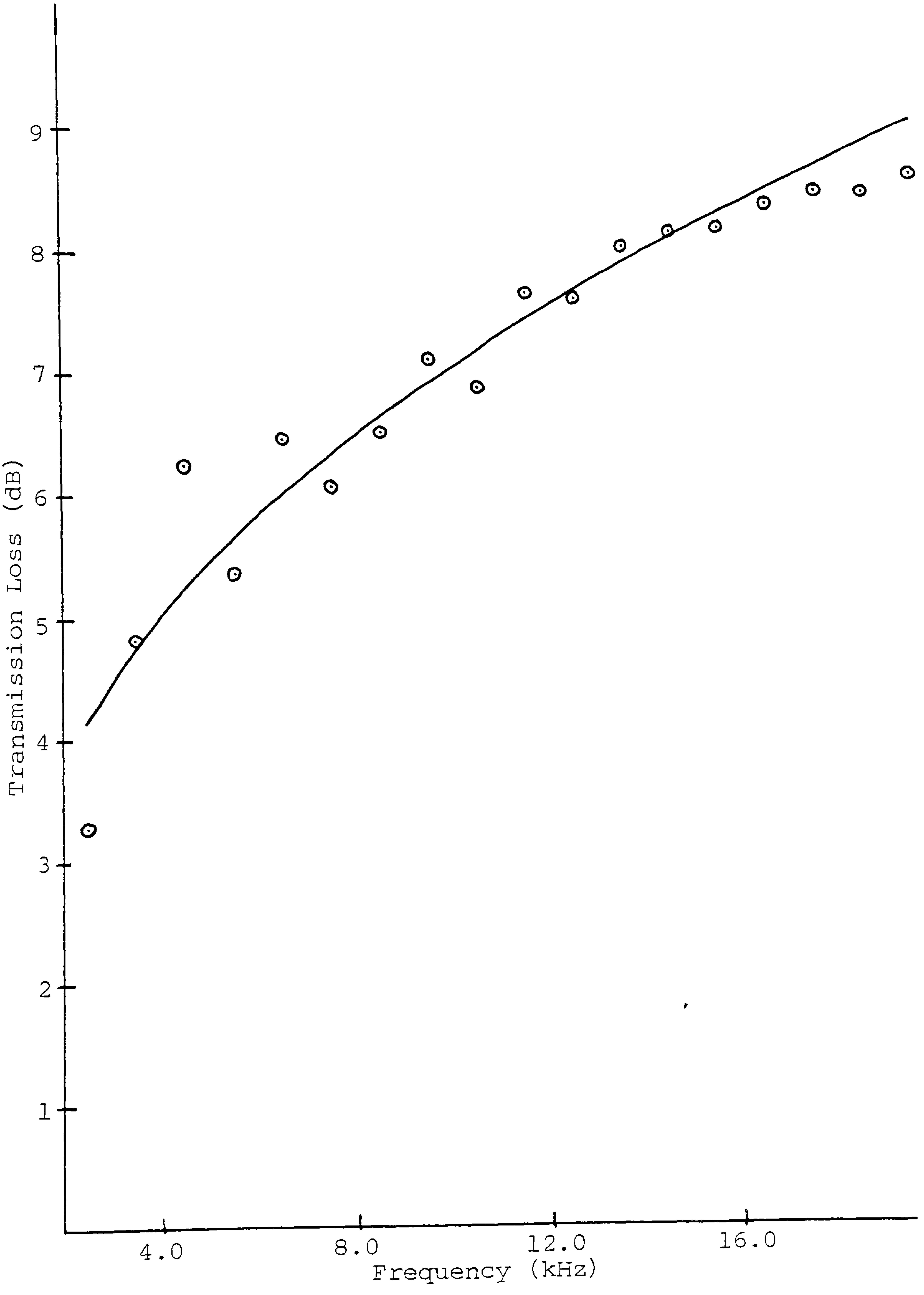


Figure A2.92 Experimental and theoretical transmission loss versus frequency for fabric G12.

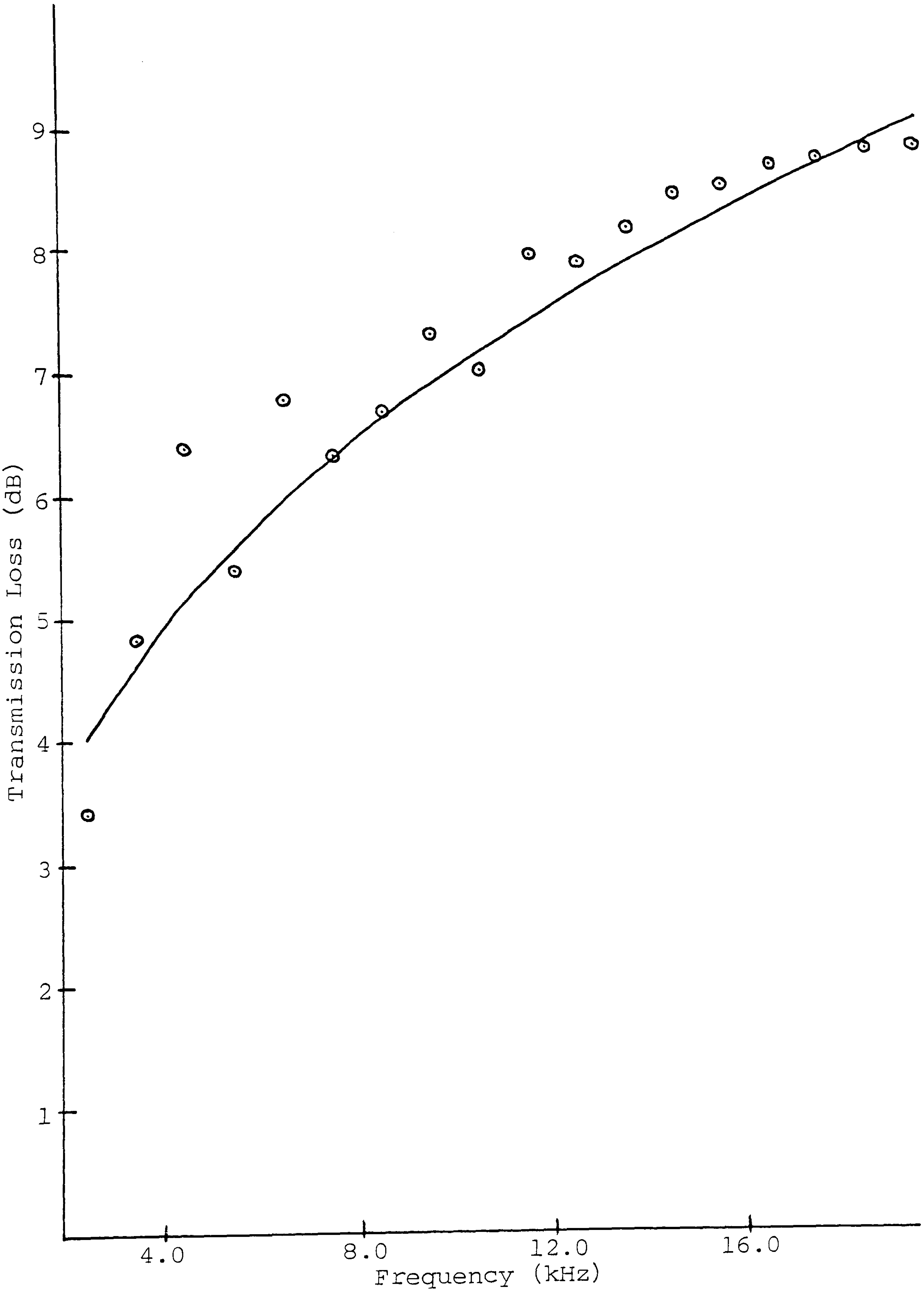


Figure A2.93 Experimental and theoretical transmission loss versus frequency for fabric G13.

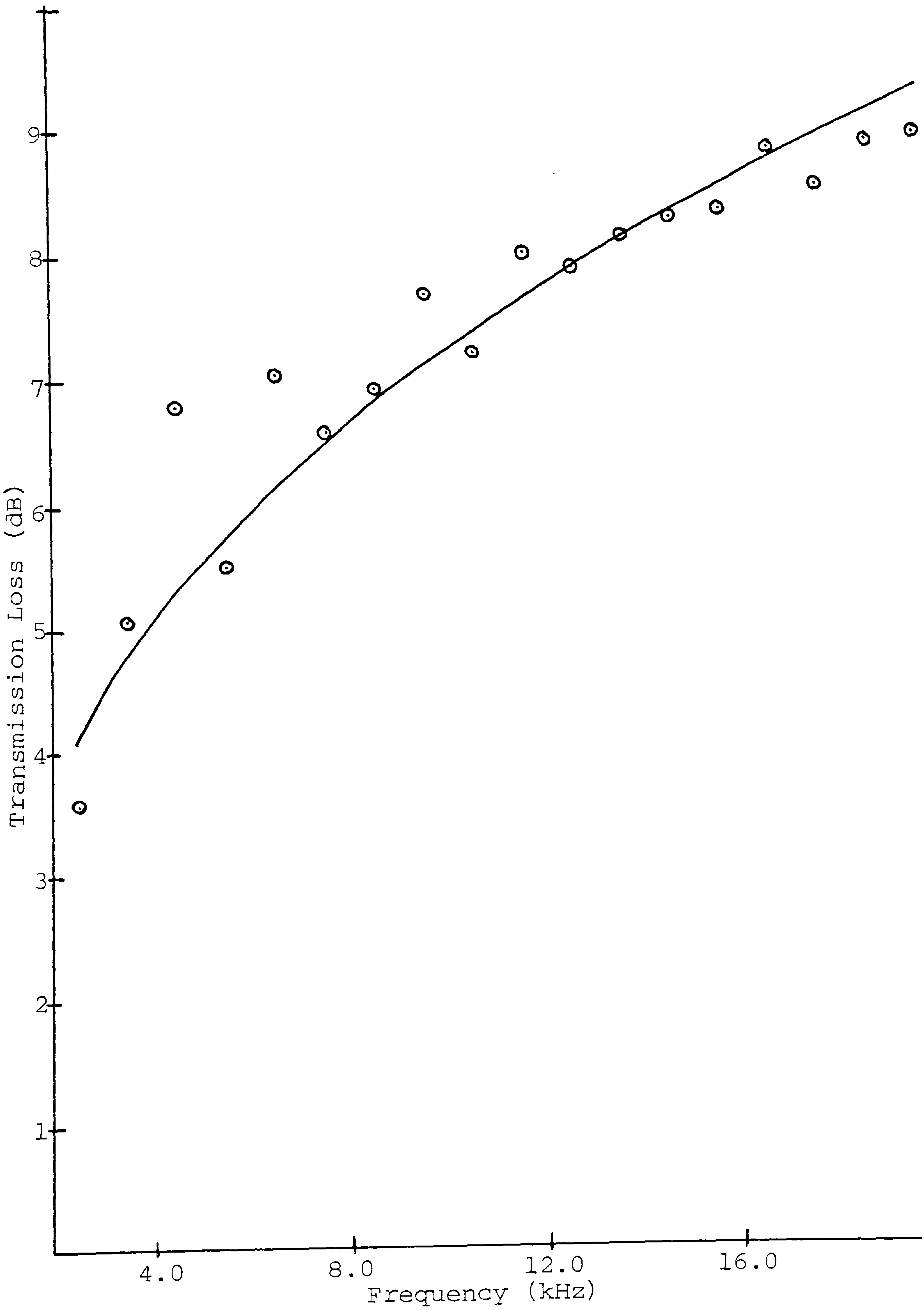


Figure A2.94 Experimental and theoretical transmission loss versus frequency for fabric G14.

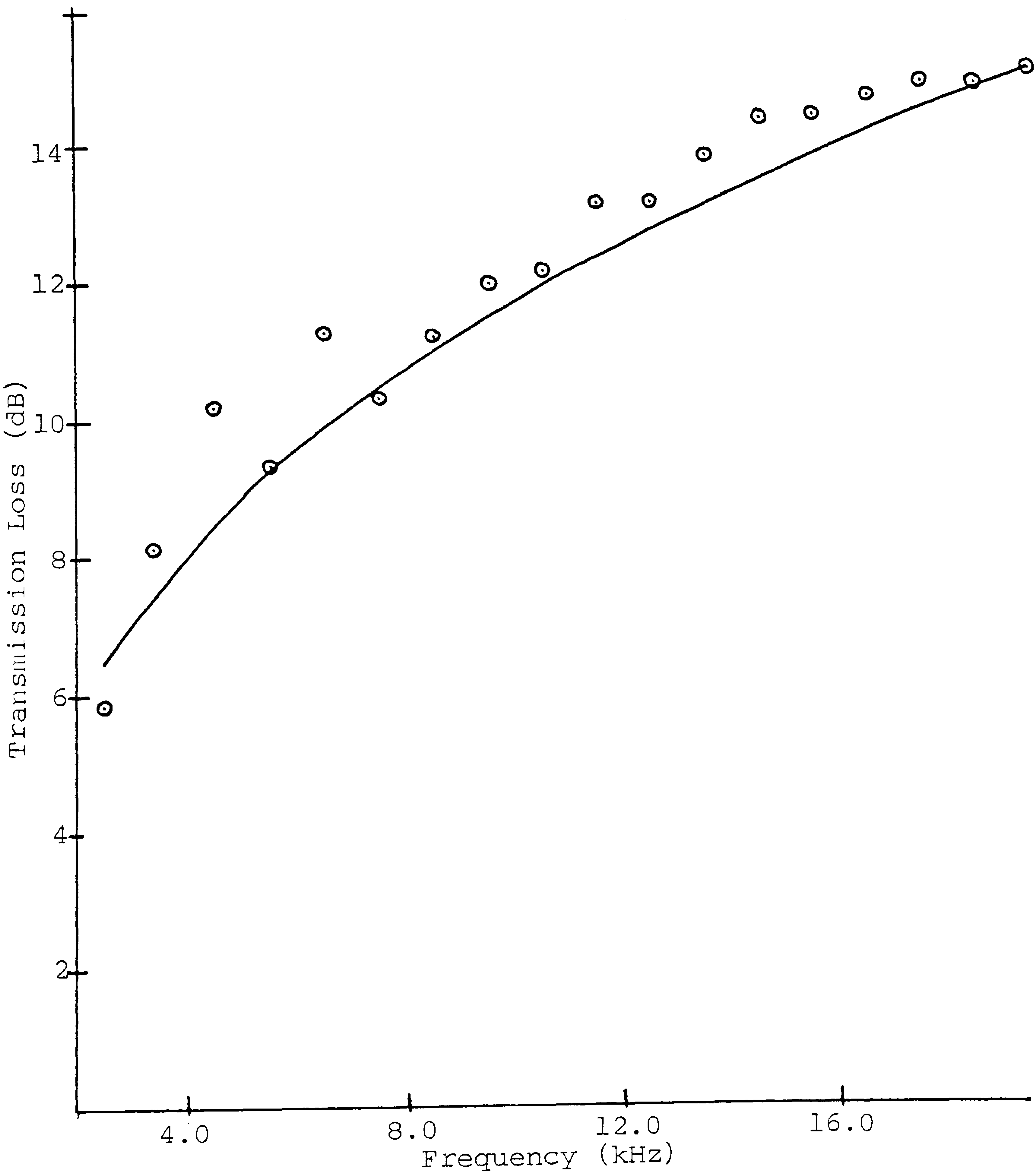


Figure A2.95 Experimental and theoretical transmission loss versus frequency for fabric H1.

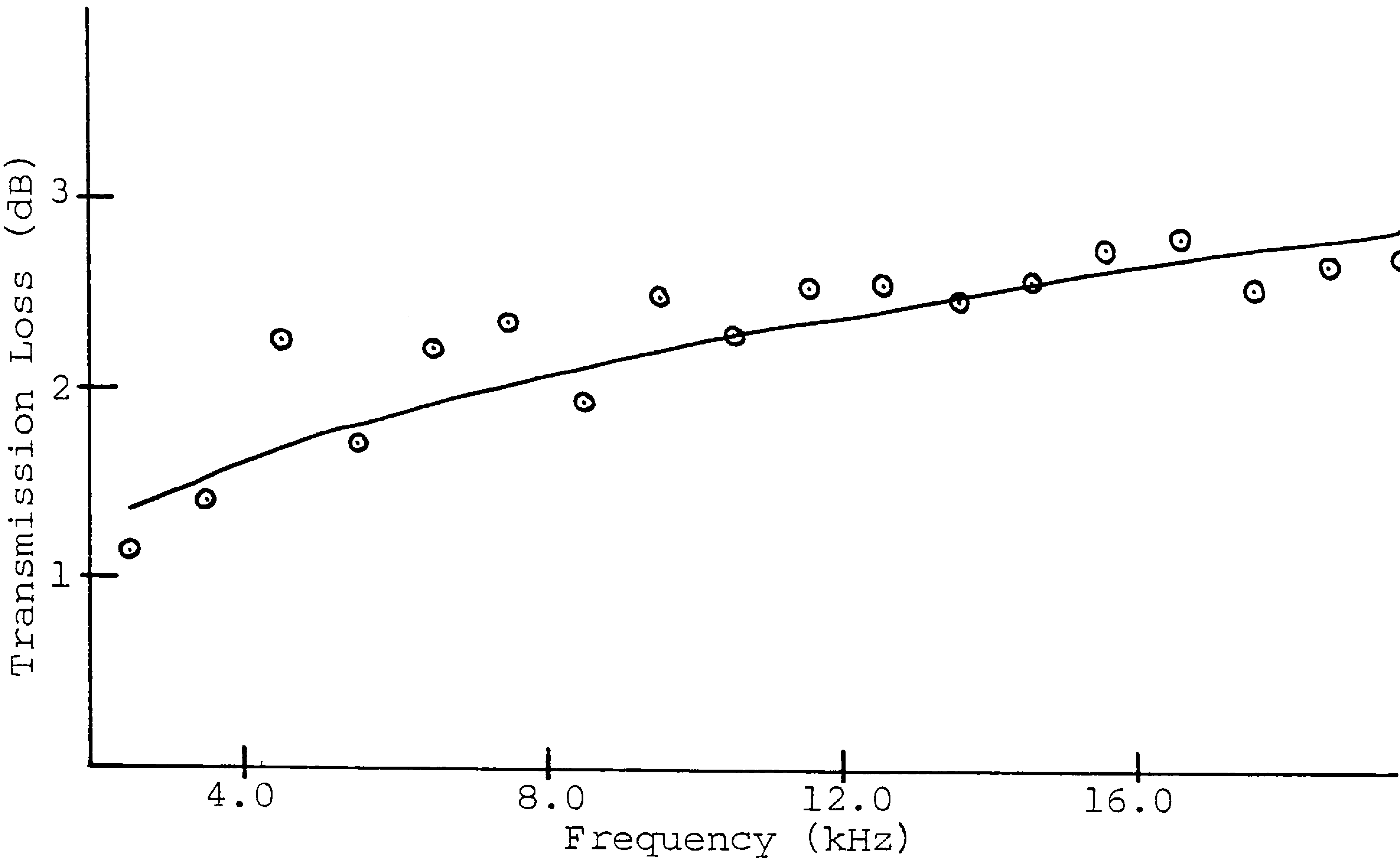


Figure A2.96 Experimental and theoretical transmission loss versus frequency for fabric H2.

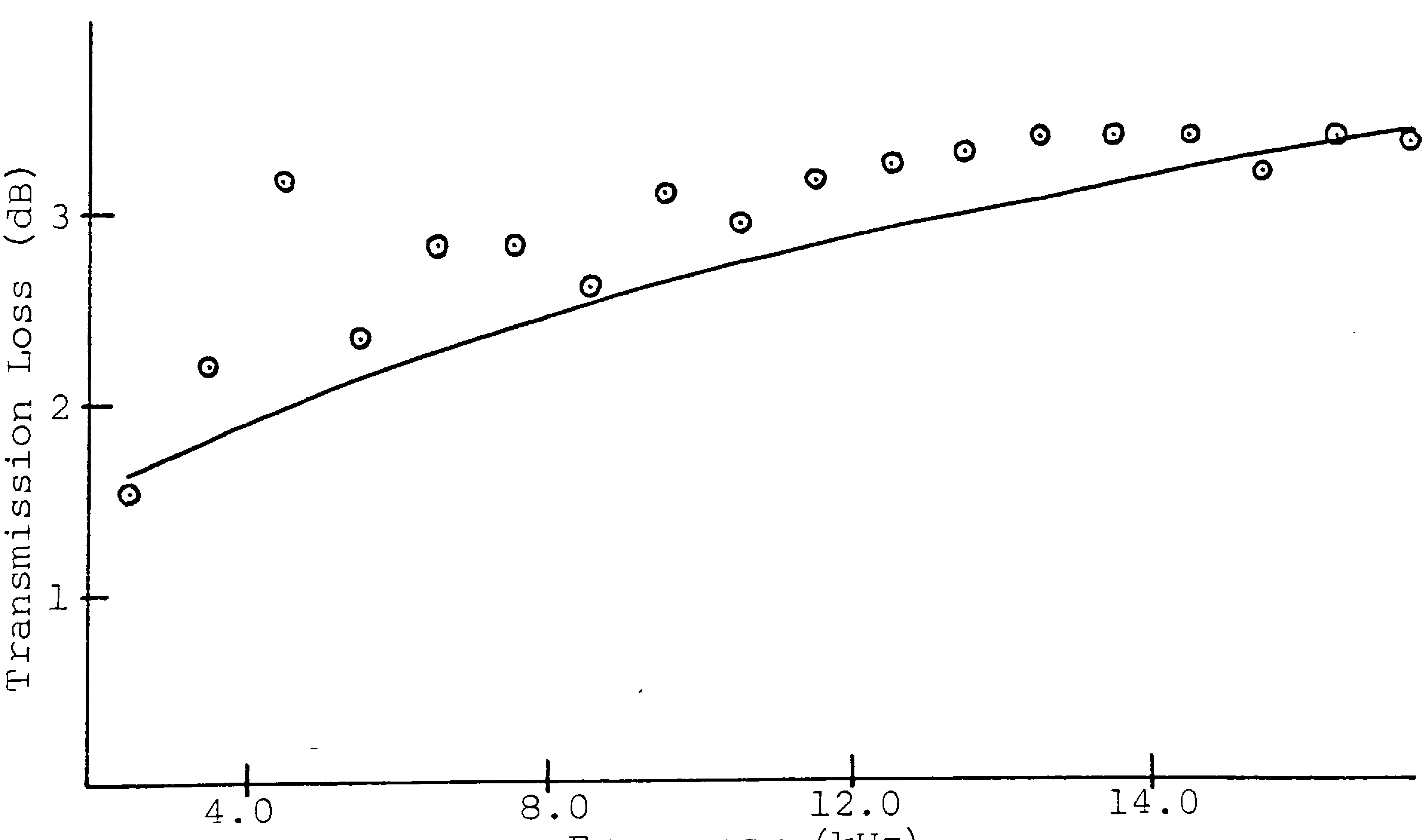


Figure A2.97 Experimental and theoretical transmission loss versus frequency for fabric H3.

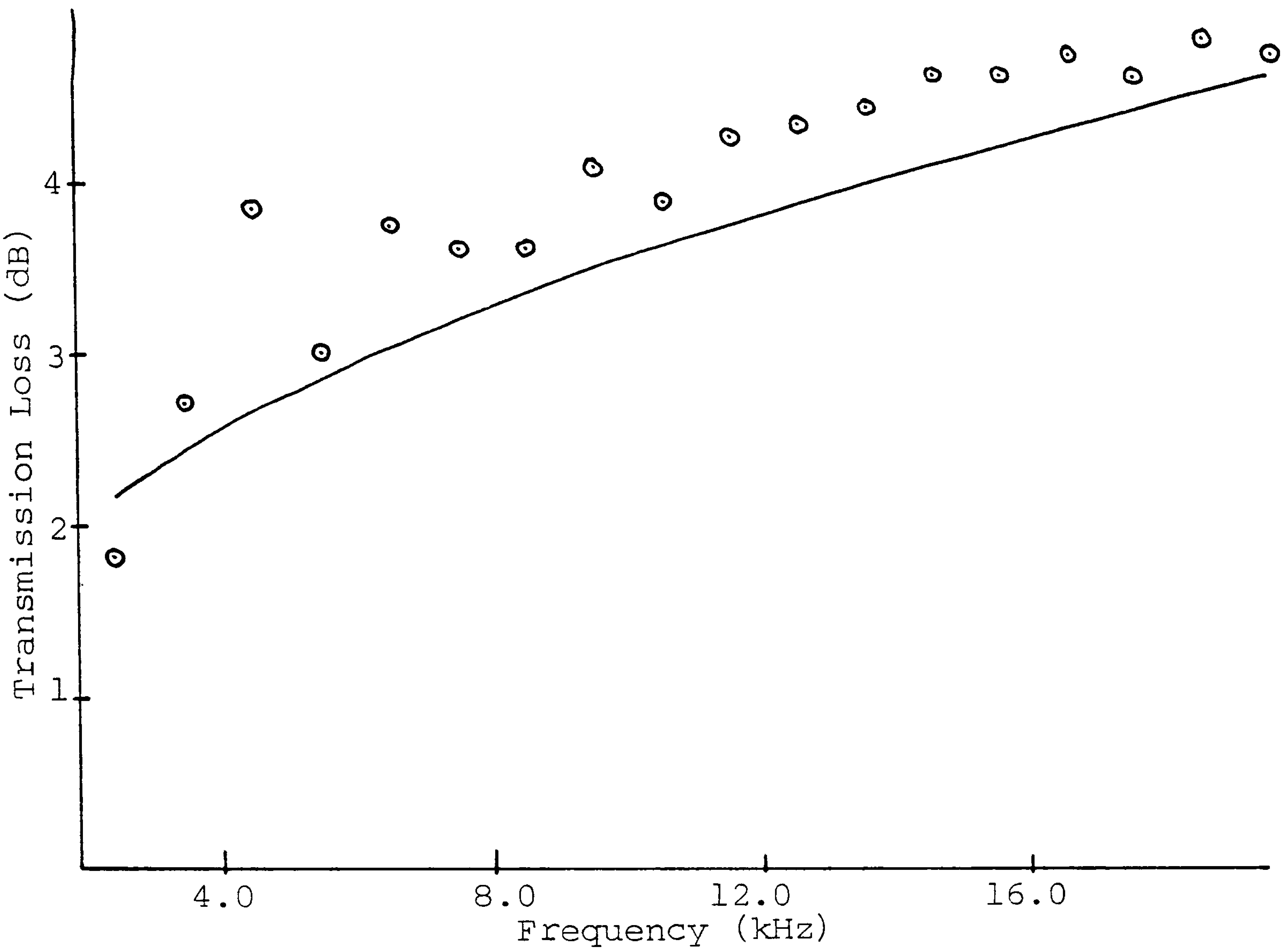


Figure A2.98 Experimental and theoretical transmission loss versus frequency for fabric H4.

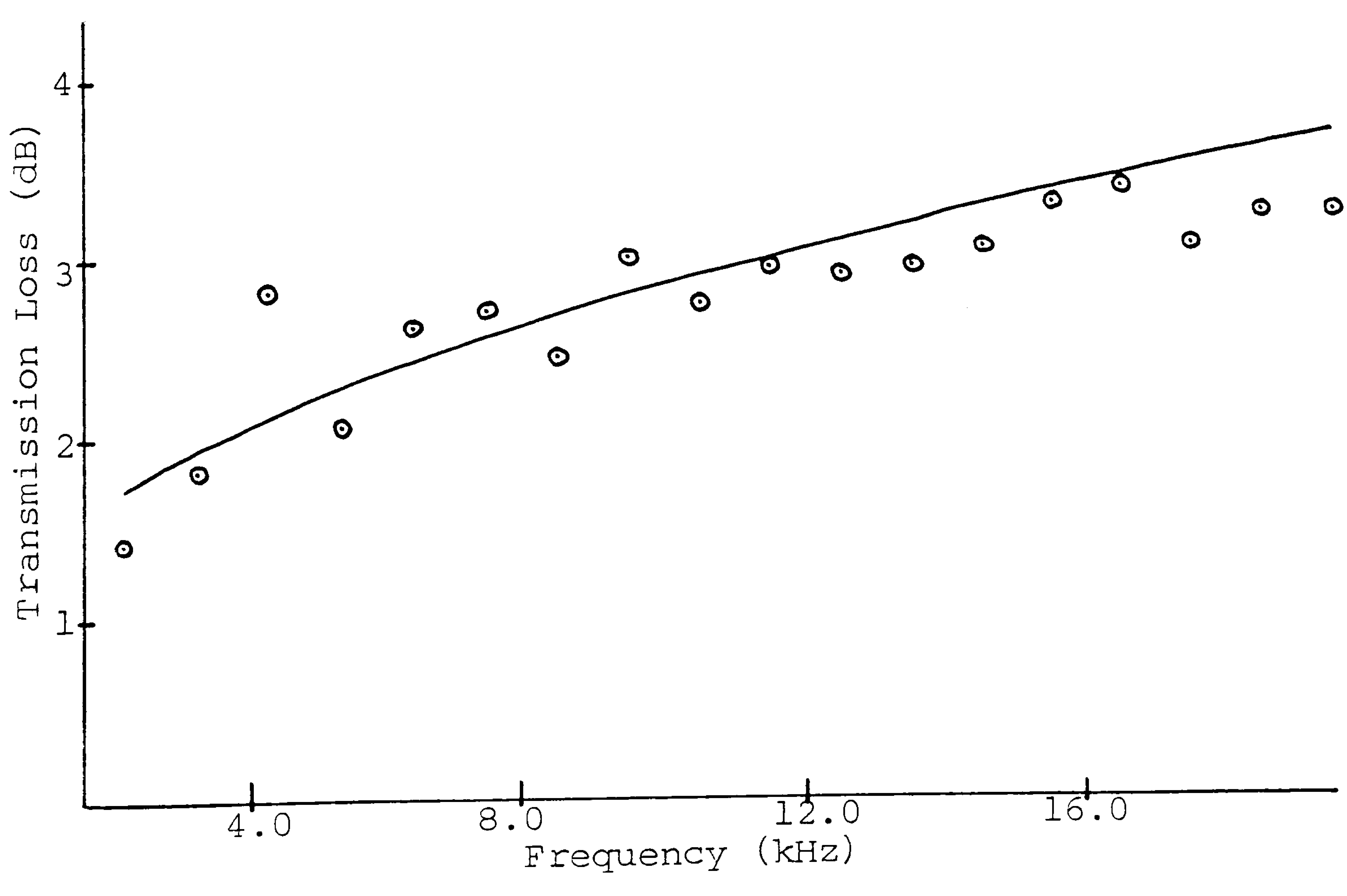


Figure A2.99 Experimental and theoretical transmission loss versus frequency for fabric H5.

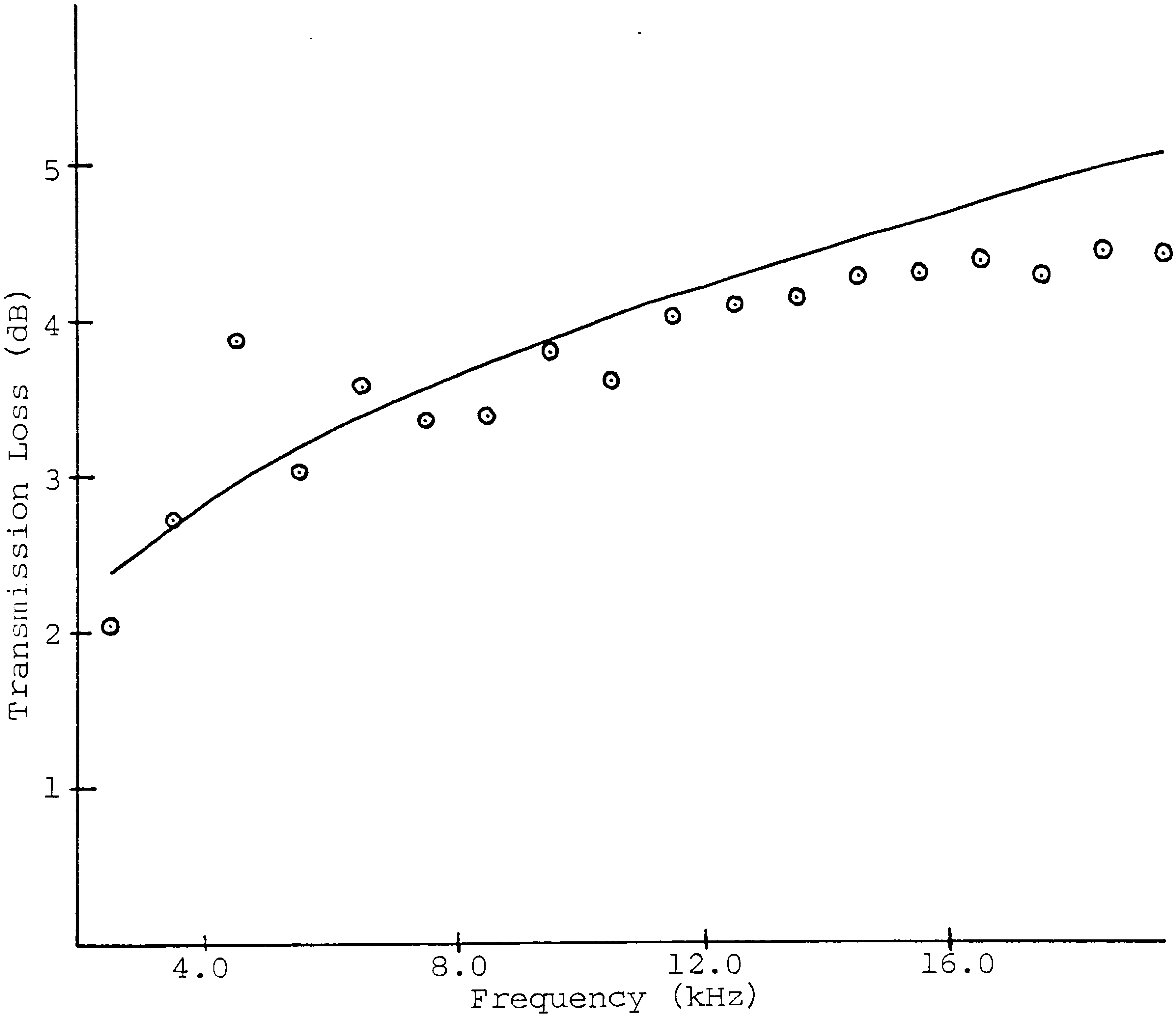


Figure A2.100 Experimental and theoretical transmission loss versus frequency for fabric H6.

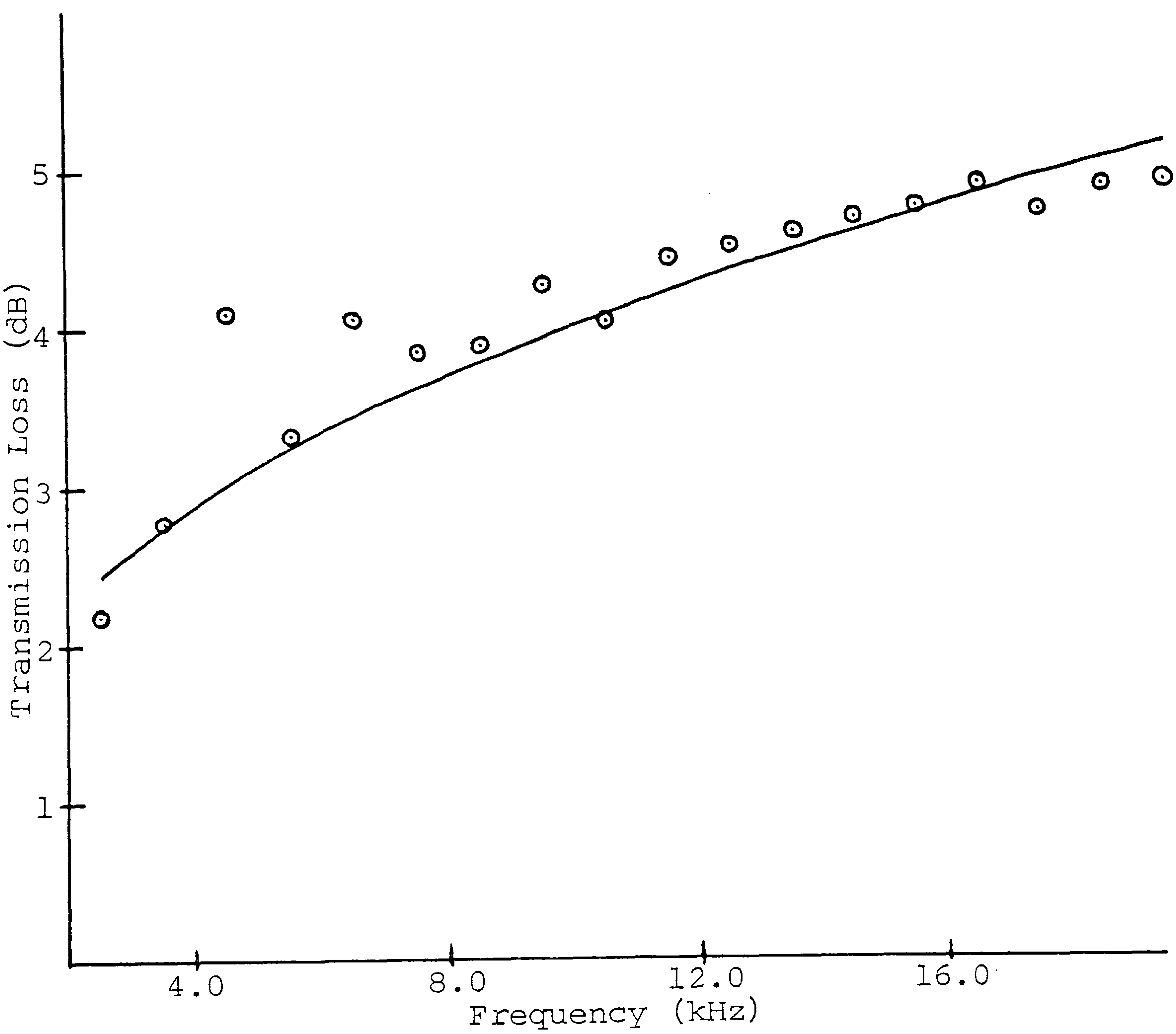


Figure A2.101 Experimental and theoretical transmission loss versus frequency for fabric H7.

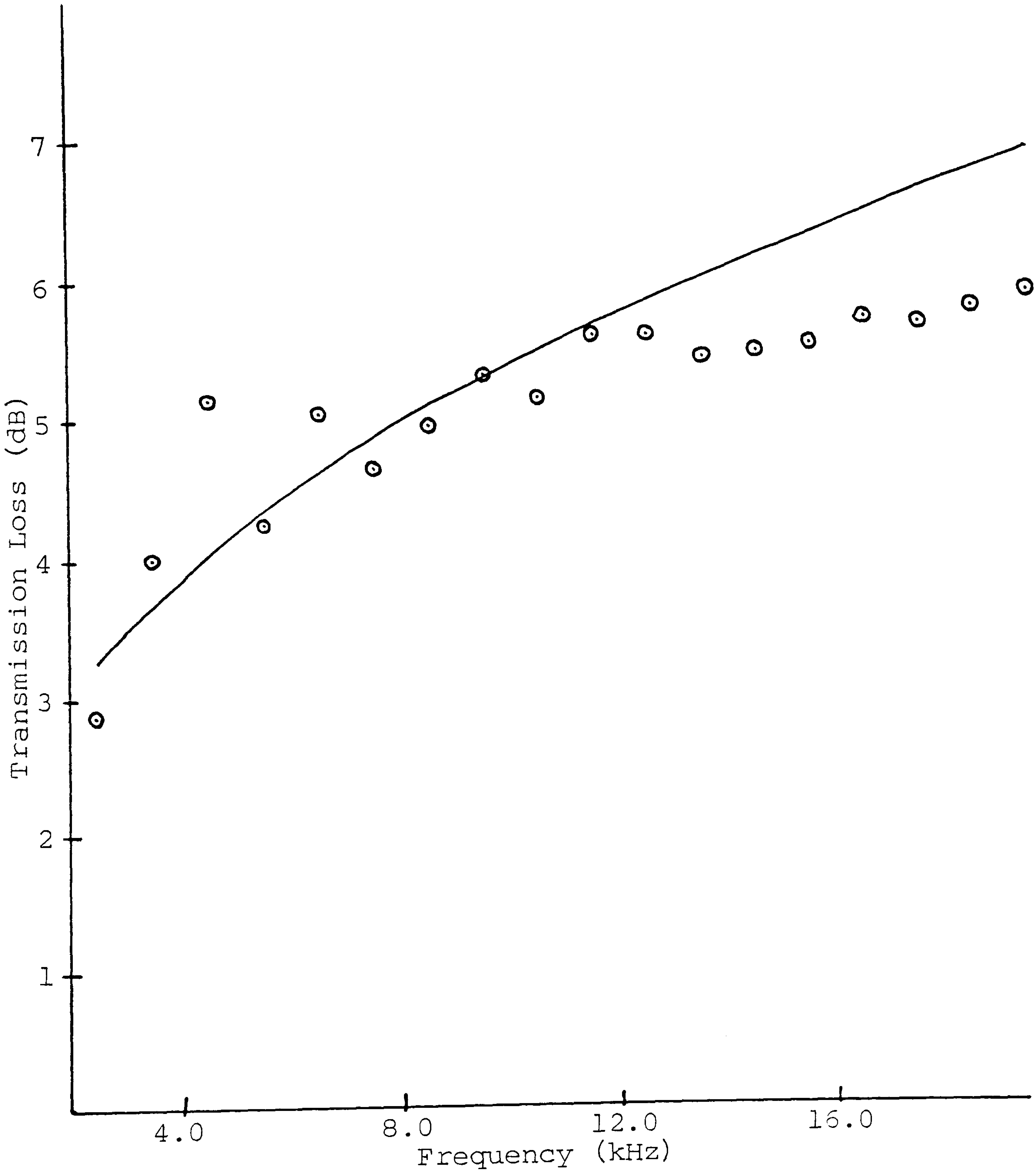


Figure A2.102 Experimental and theoretical transmission loss versus frequency for fabric I1.

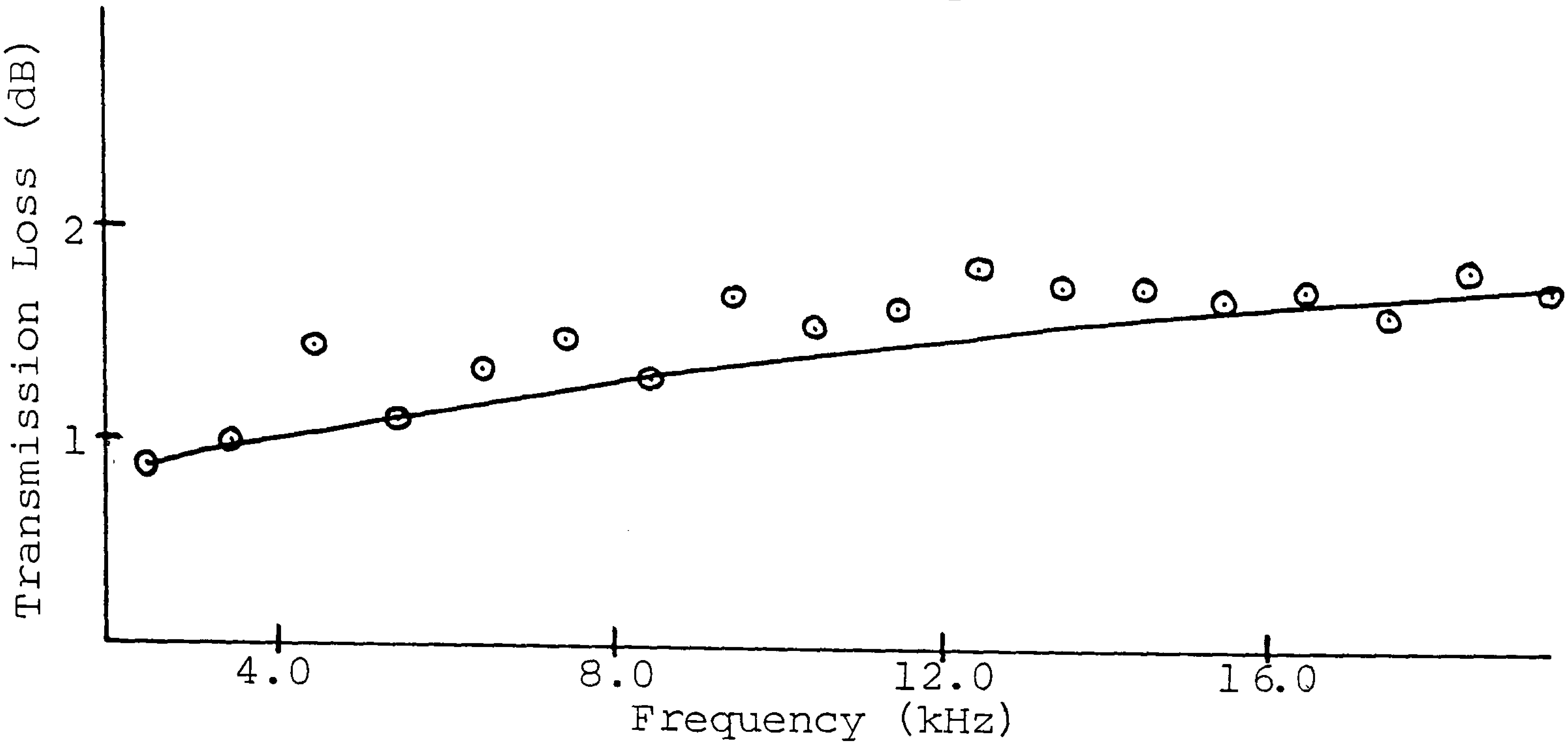


Figure A2.103 Experimental and theoretical transmission loss versus frequency for fabric I2.

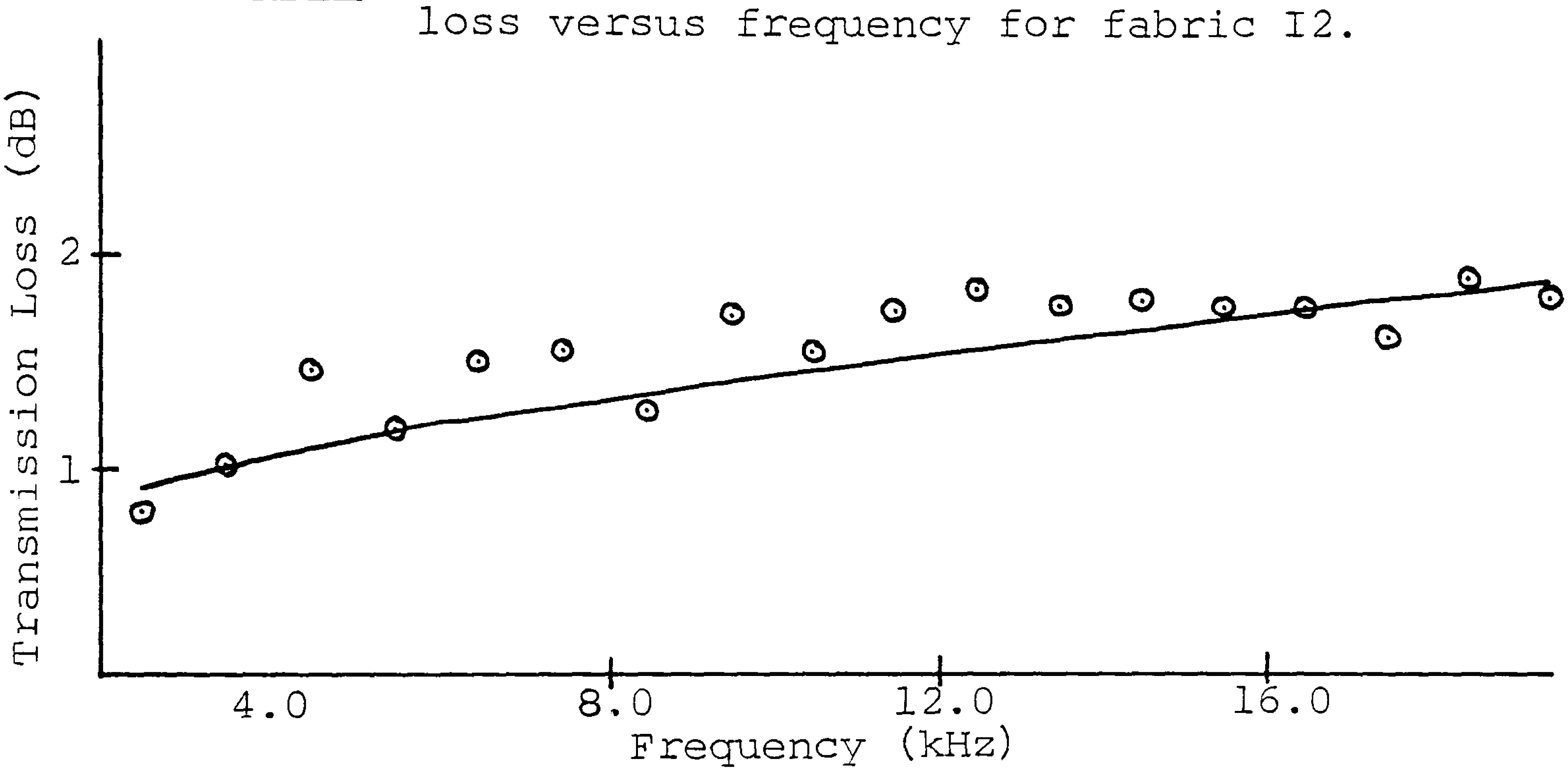


Figure A2.104 Experimental and theoretical transmission loss versus frequency for fabric I3.

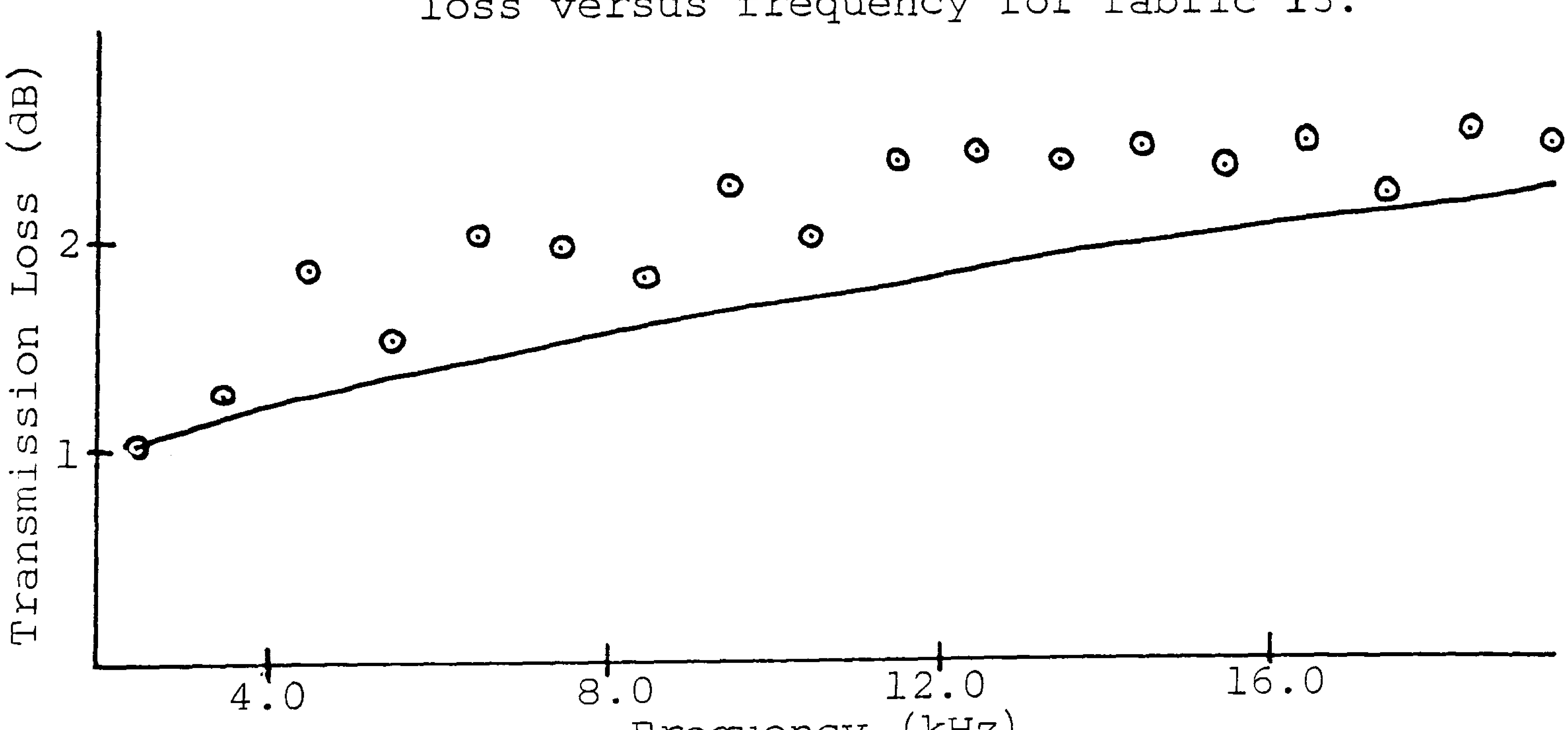


Figure A2.105 Experimental and theoretical transmission loss versus frequency for fabric I4.

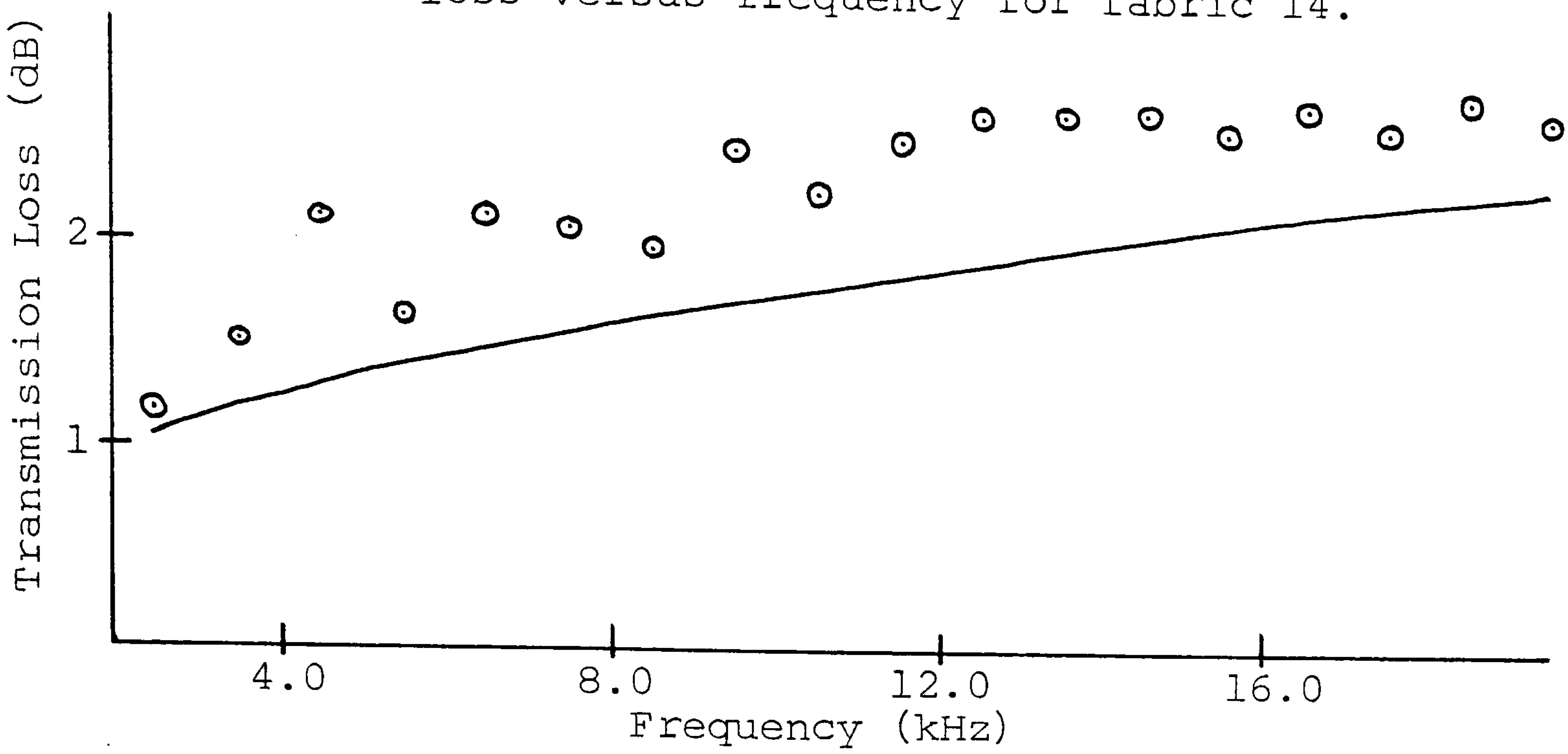


Figure A2.106 Experimental and theoretical transmission loss versus frequency for fabric I5.

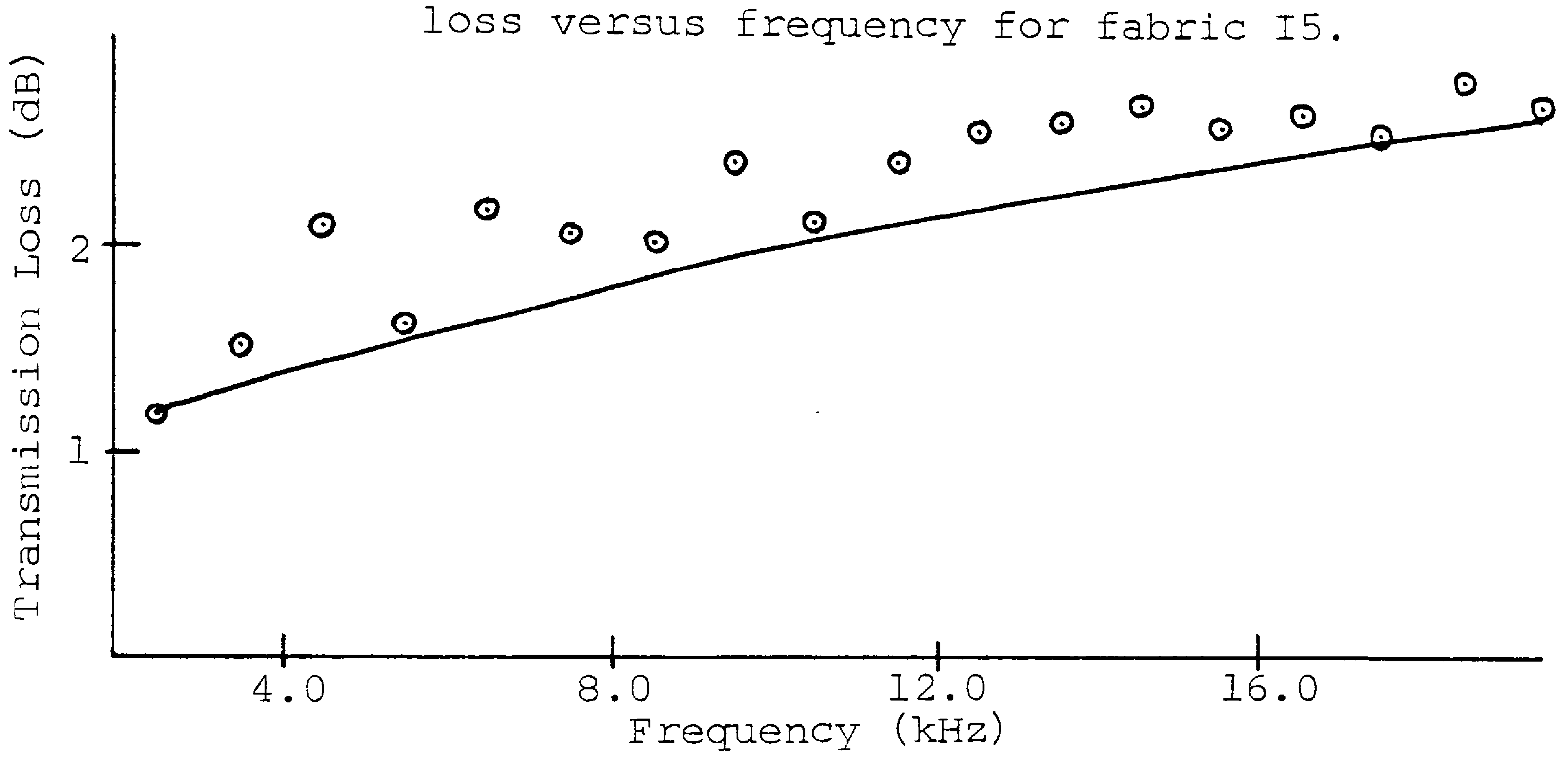


Figure A2.107 Experimental and theoretical transmission loss versus frequency for fabric I6.

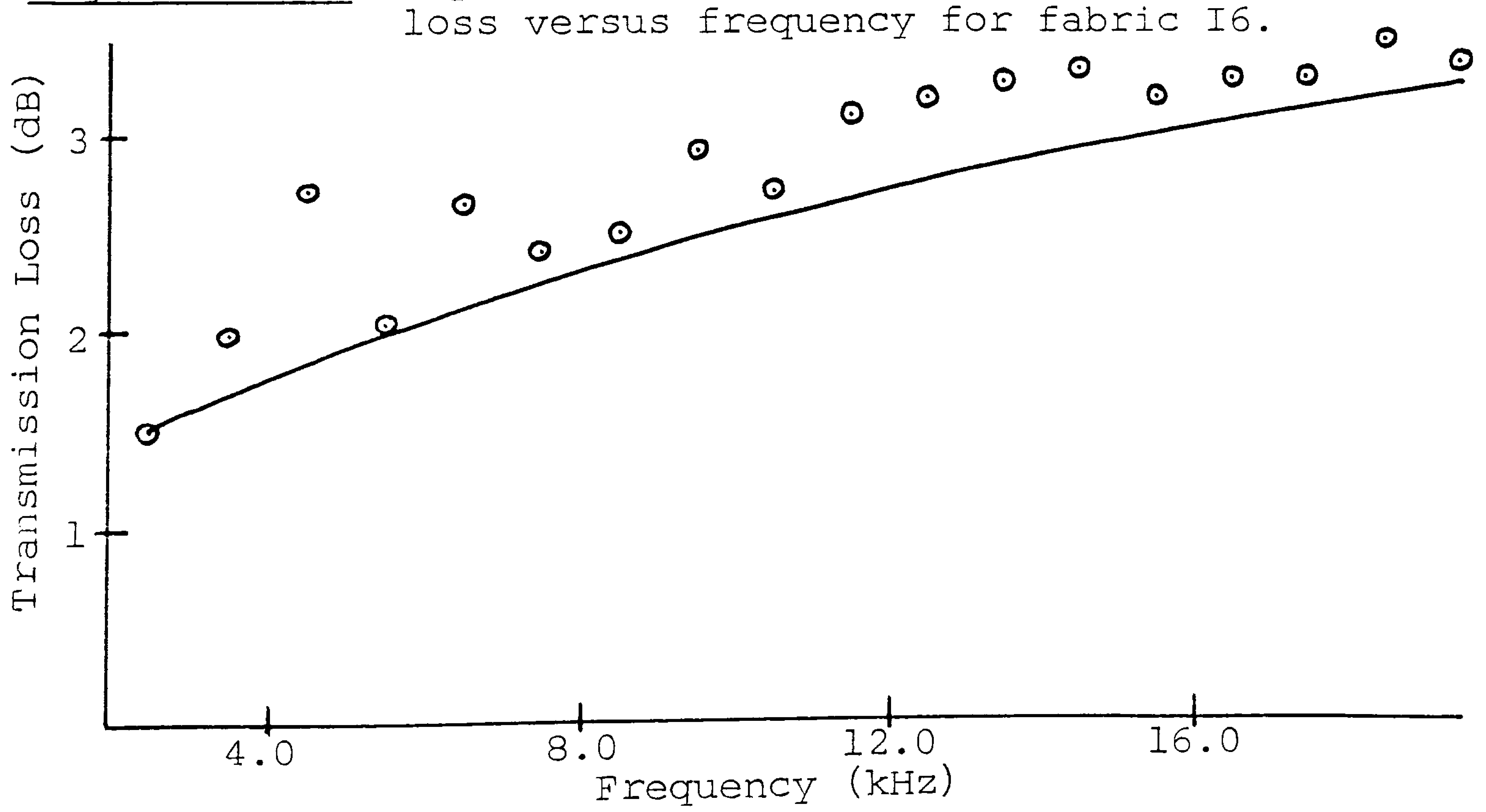


Figure A2.108 Experimental and theoretical transmission loss versus frequency for fabric I7.

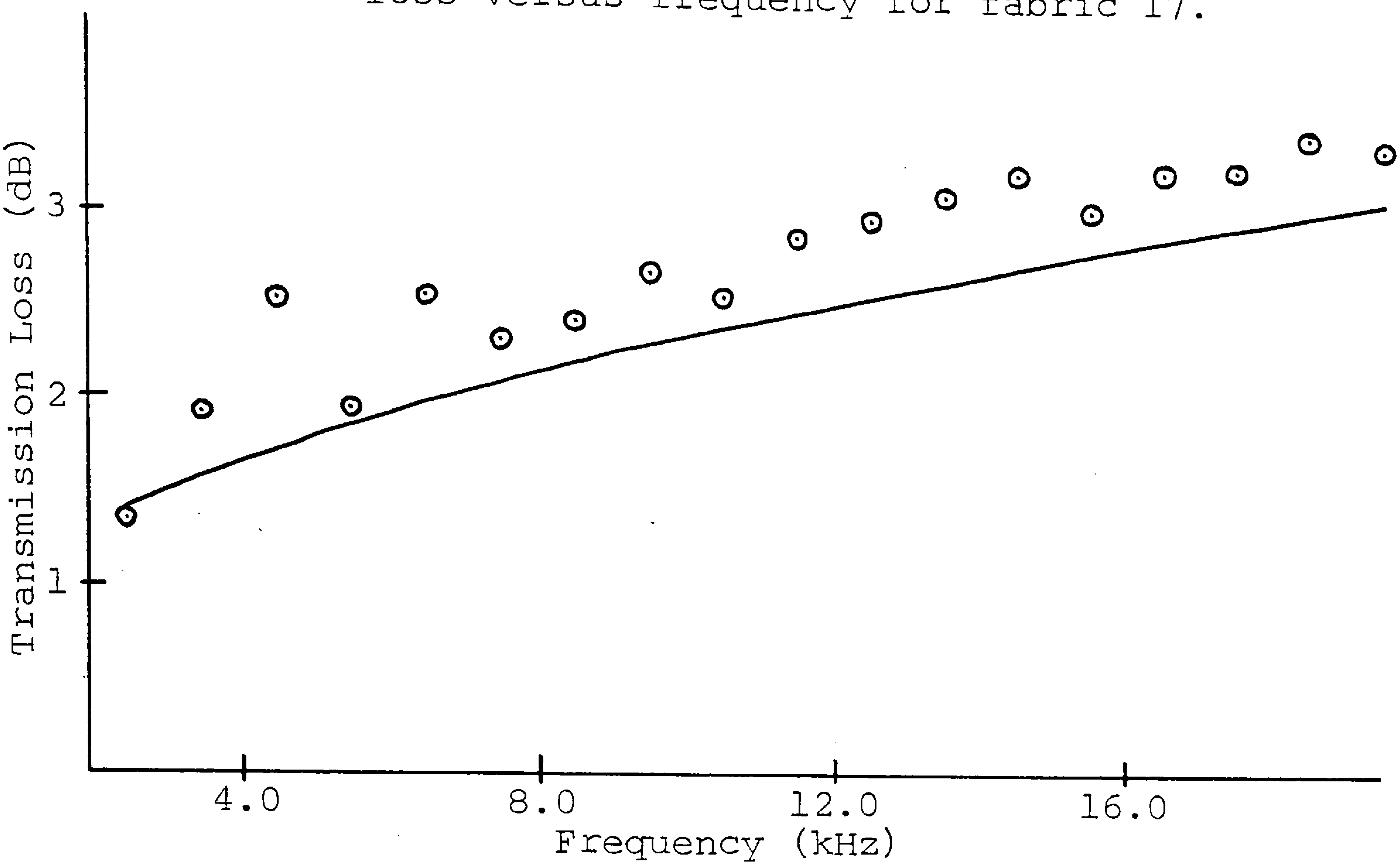


Figure A2.109 Experimental and theoretical transmission loss versus frequency for fabric I8.

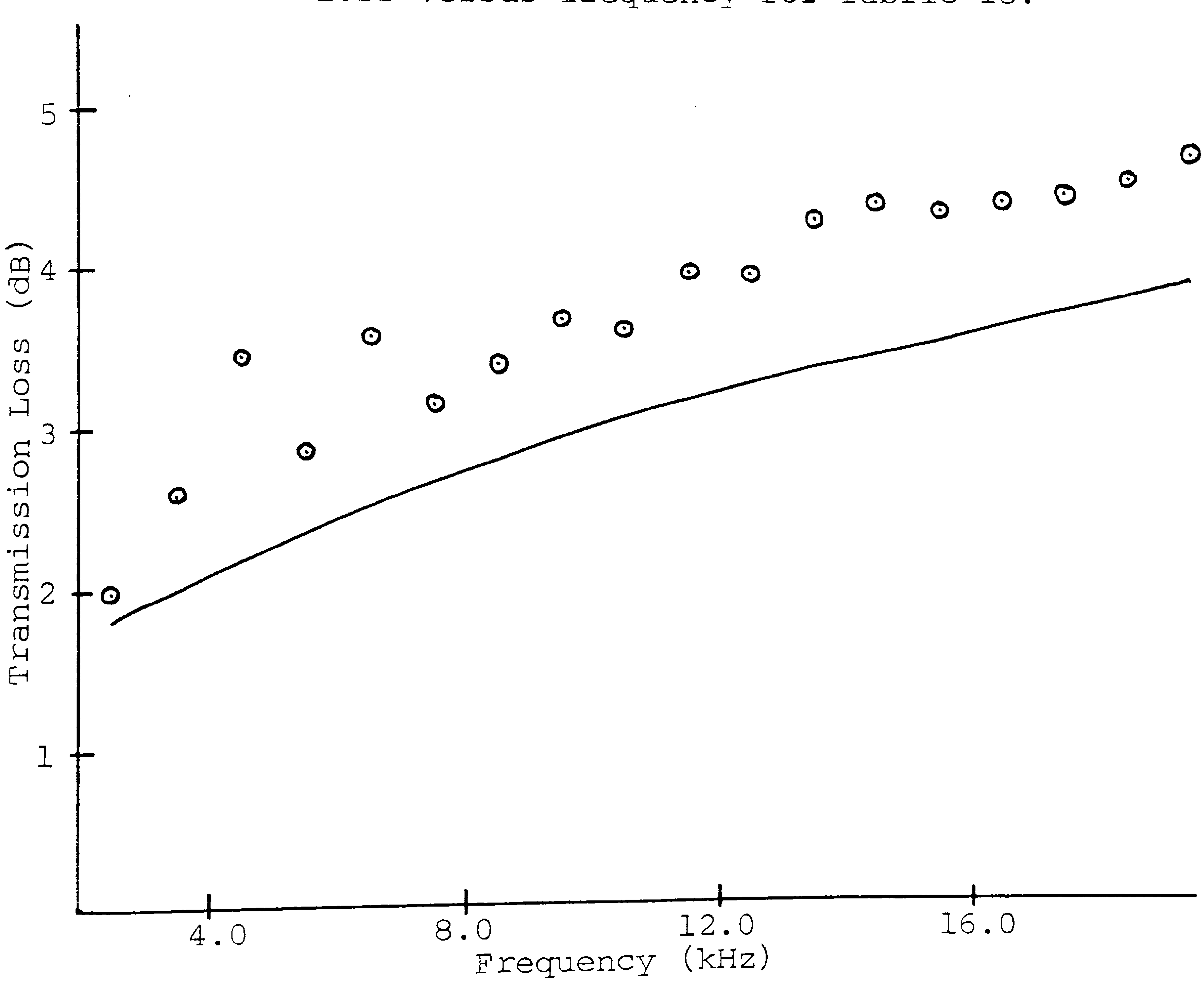


Figure A2.110 Experimental and theoretical transmission loss versus frequency for fabric J1

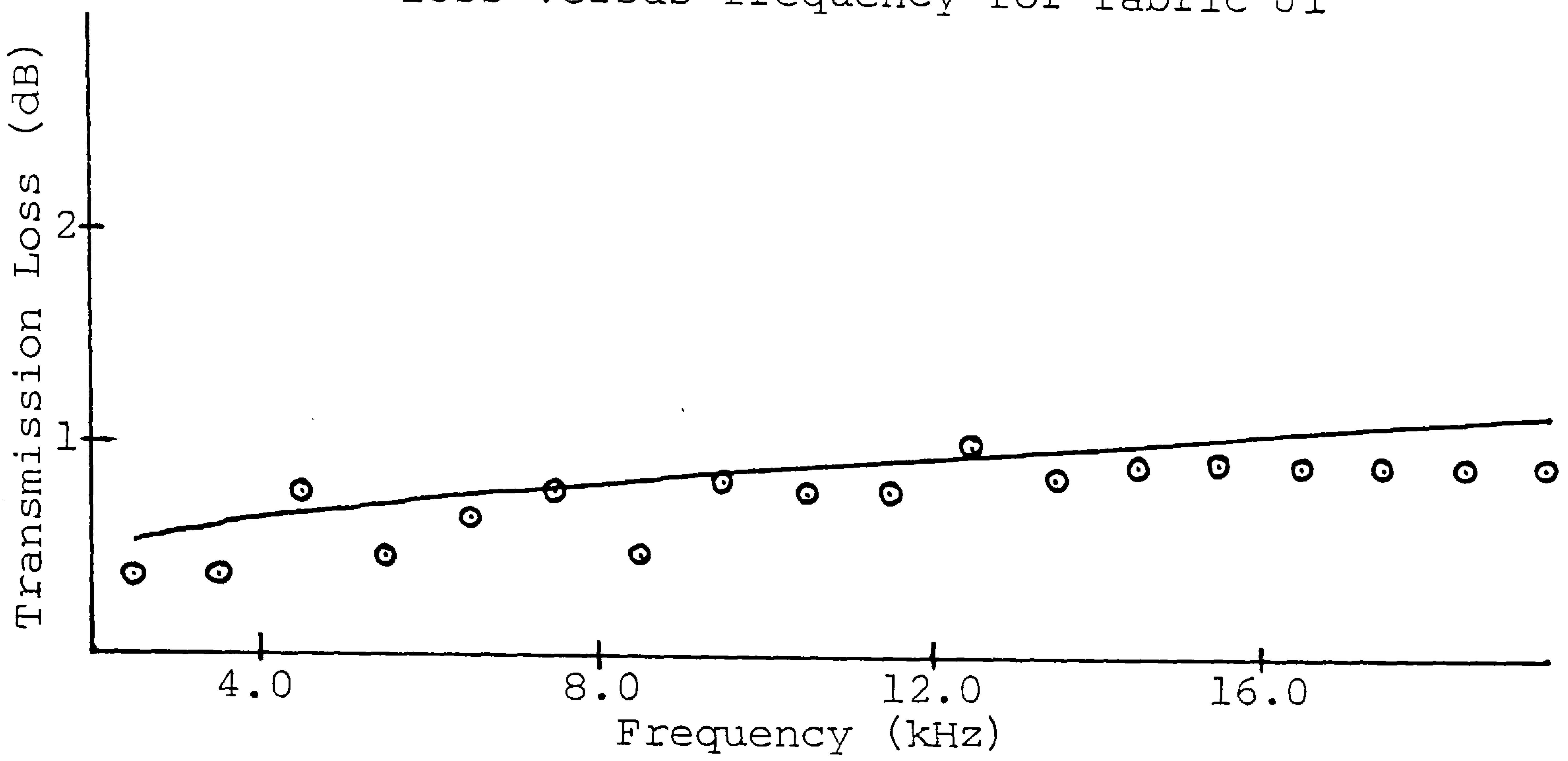


Figure A2.111 Experimental and theoretical transmission loss versus frequency for fabric J2.

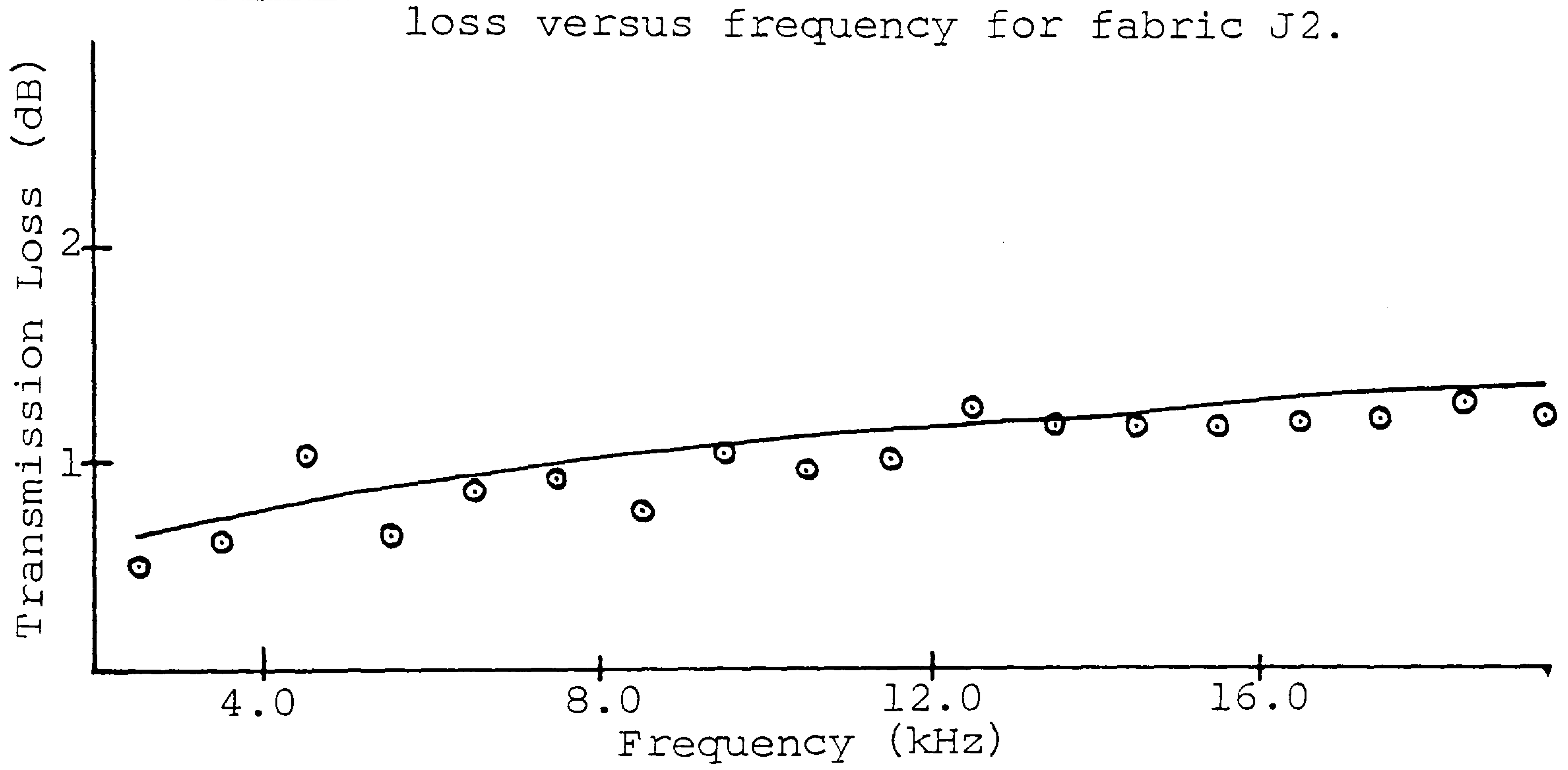


Figure A2.112 Experimental and theoretical transmission loss versus frequency for fabric J3.

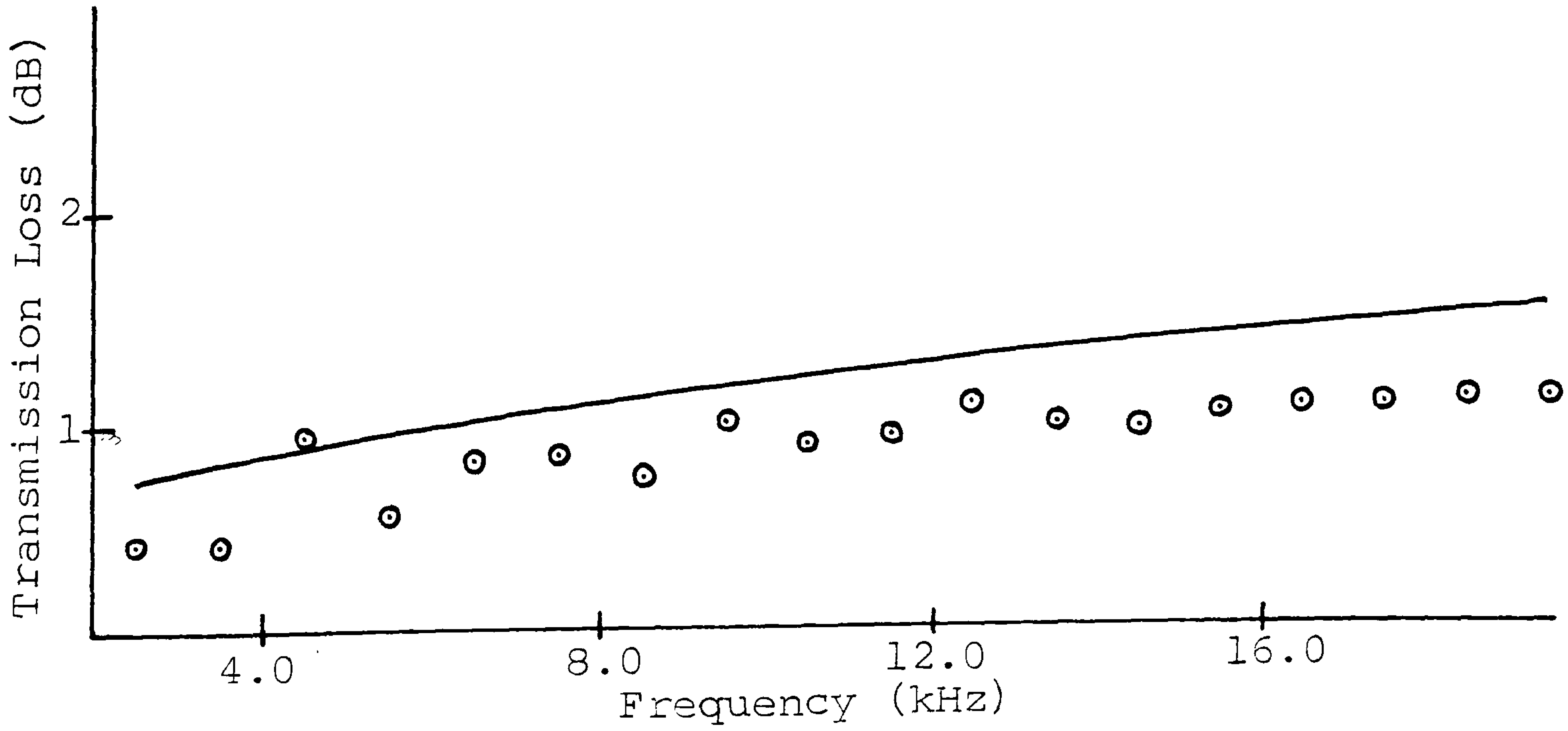


Figure A2.113 Experimental and theoretical transmission loss versus frequency for fabric J4.

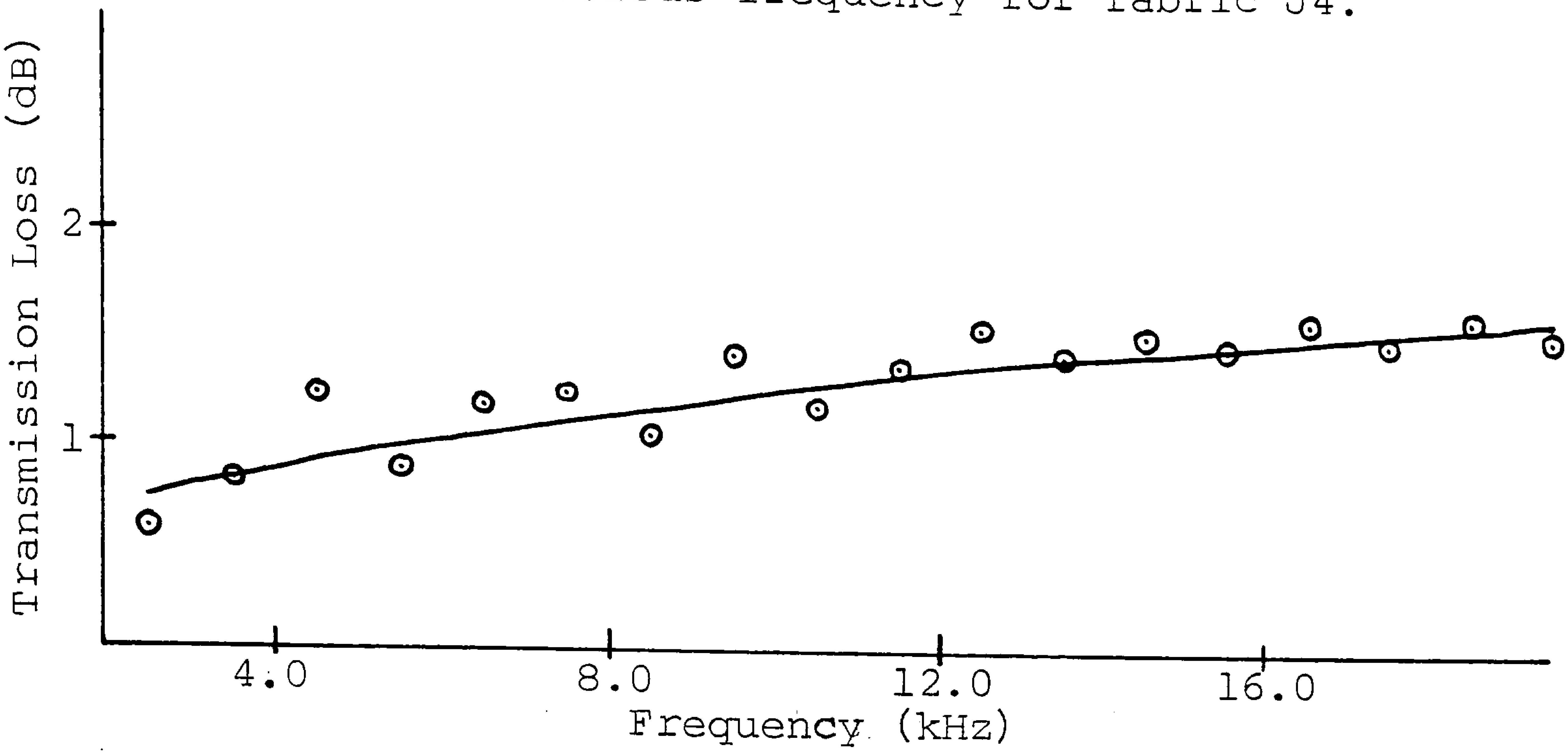


Figure A2.114 Experimental and theoretical transmission loss versus frequency for fabric J5.

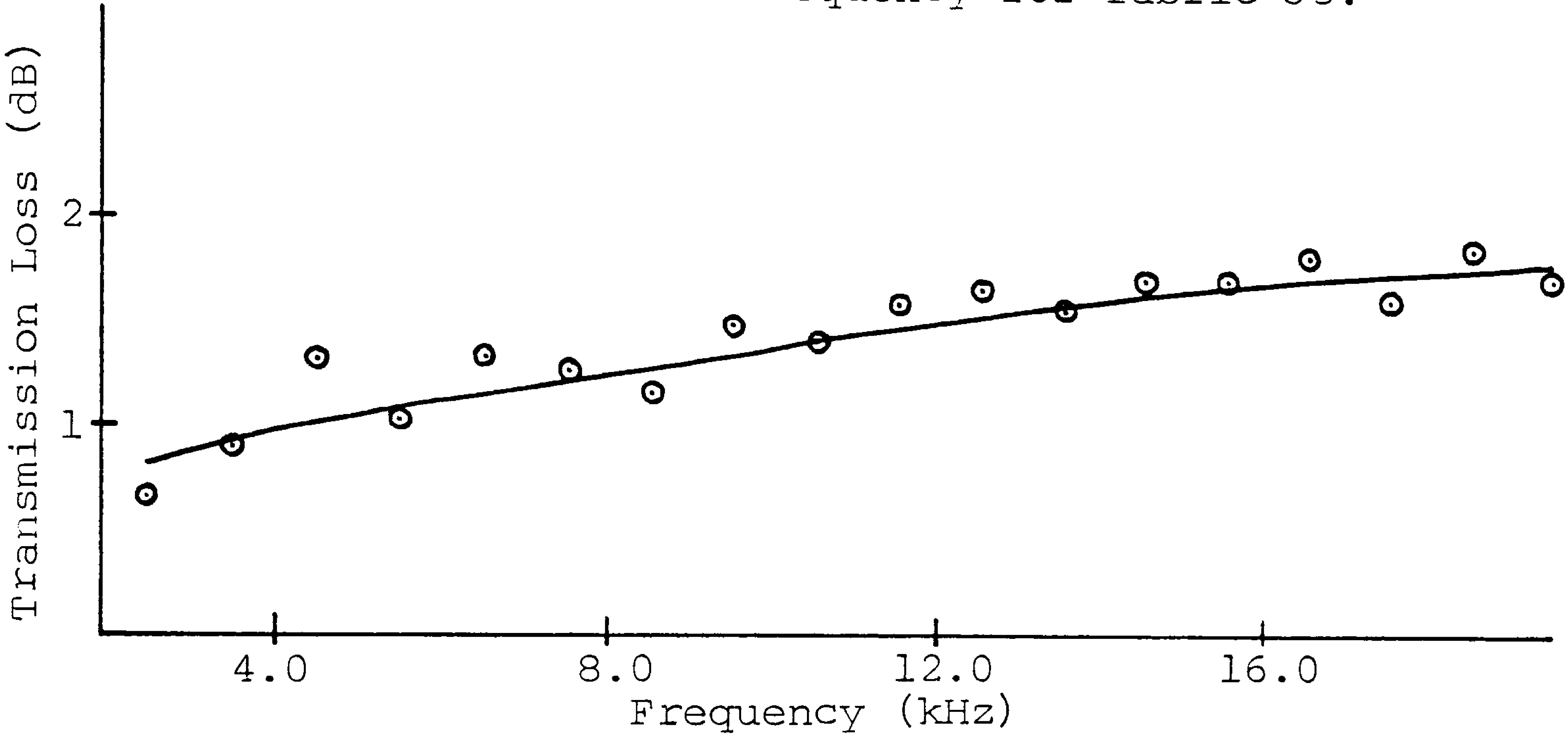


Figure A2.115 Experimental and theoretical transmission loss versus frequency for fabric J6.

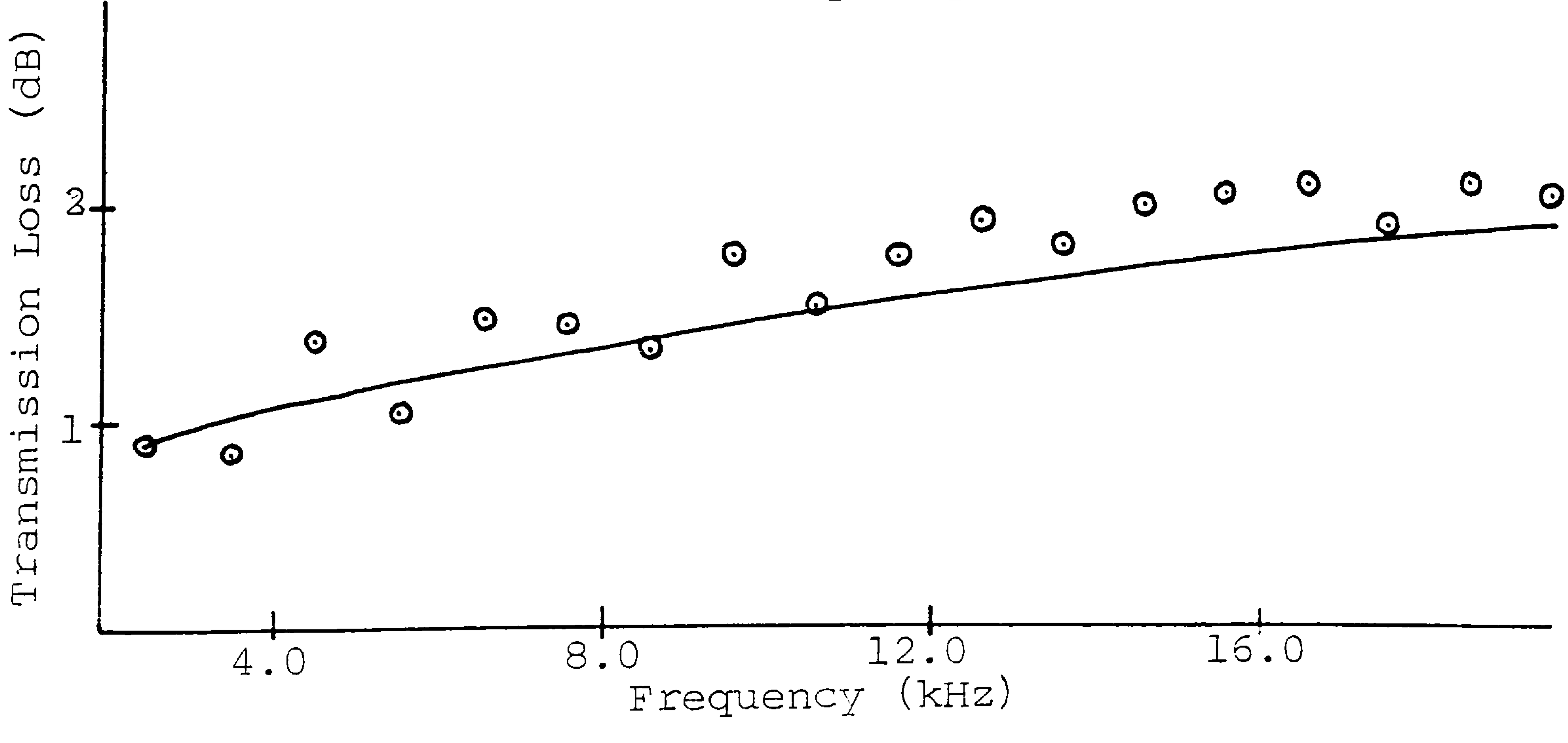


Figure A2.116 Experimental and theoretical transmission loss versus frequency for fabric J7.

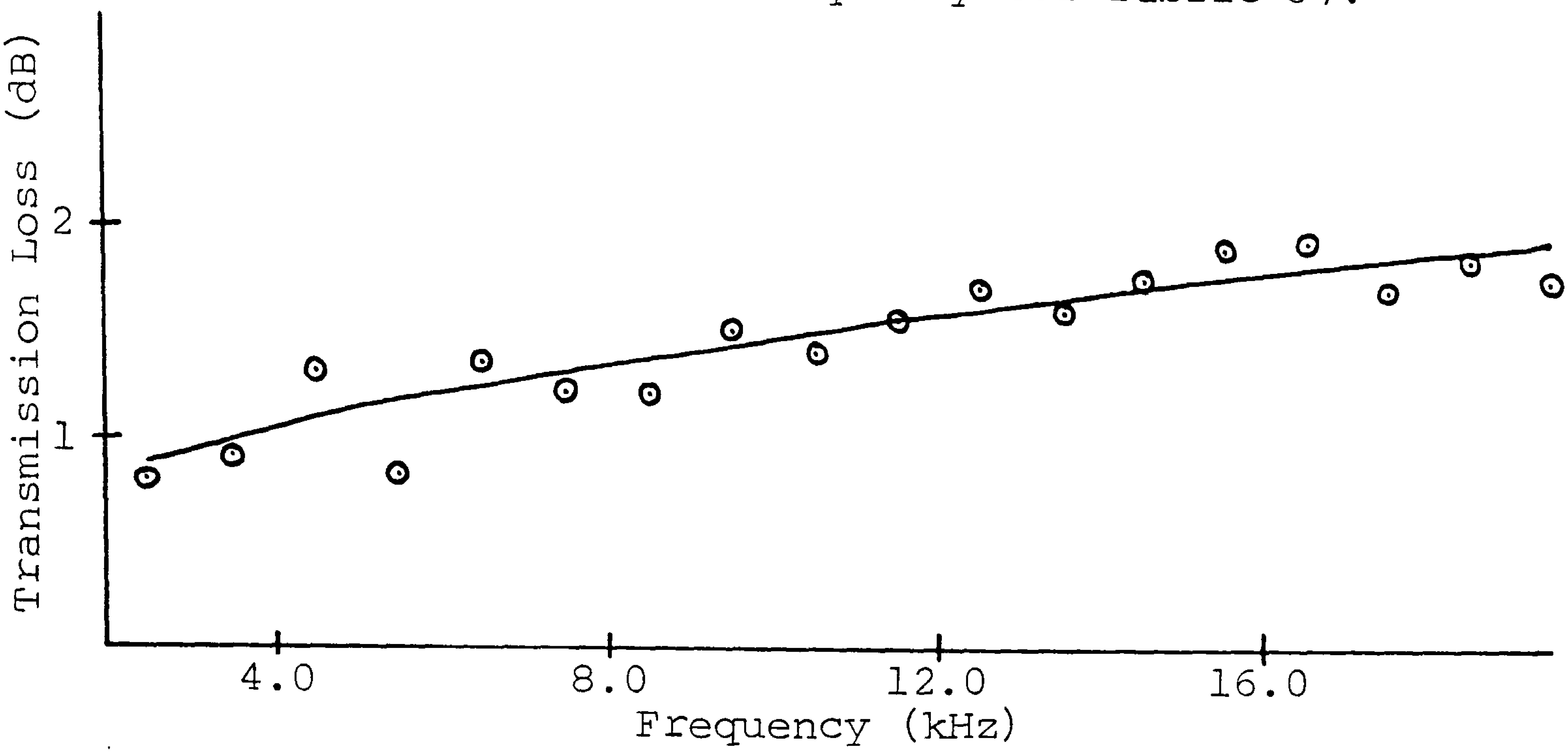


Figure A2.117 Experimental and theoretical transmission loss versus frequency for fabric J8.

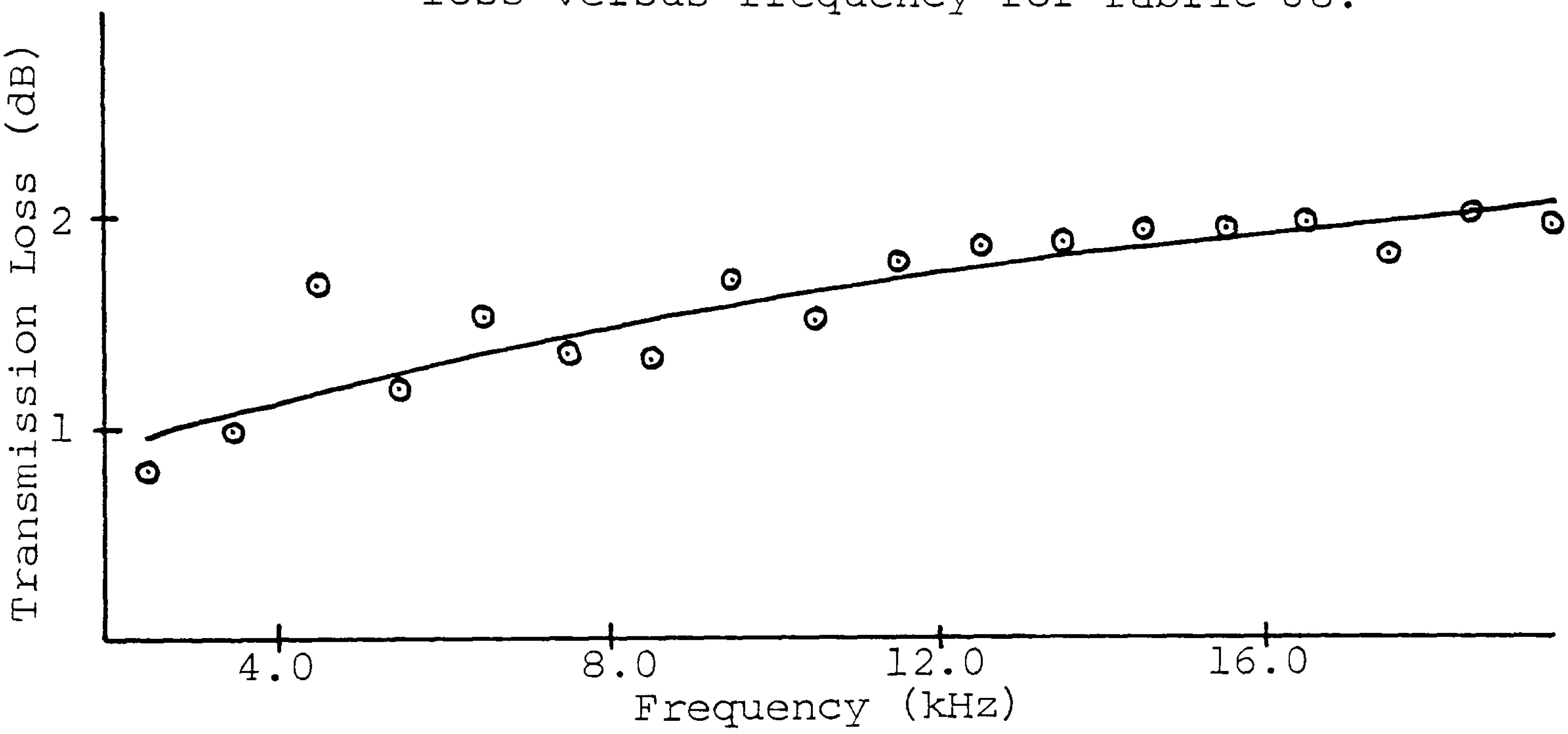


Figure A2.118 Experimental and theoretical transmission loss versus frequency for fabric J9.

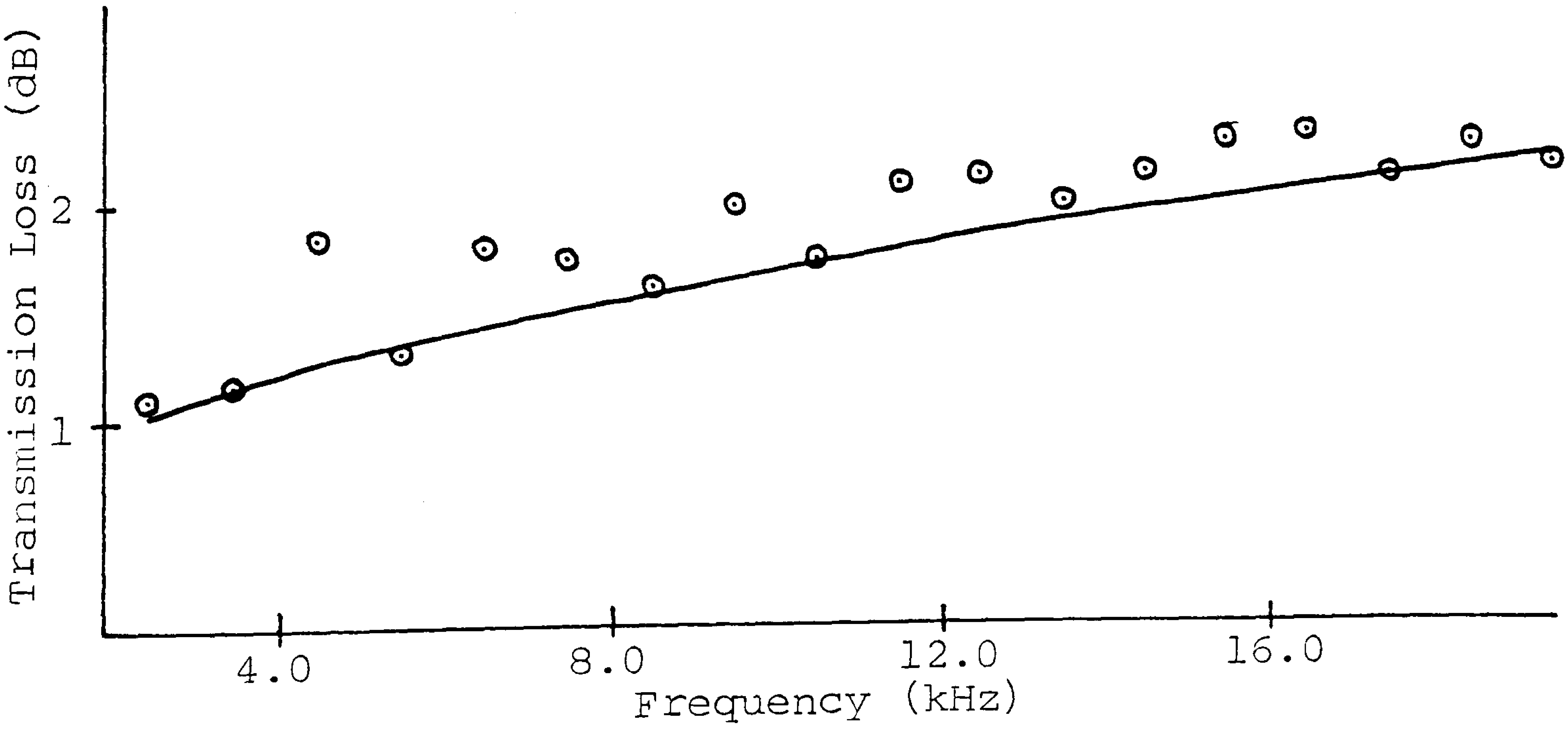


Figure A2.119 Experimental and theoretical transmission loss versus frequency for fabric J10.

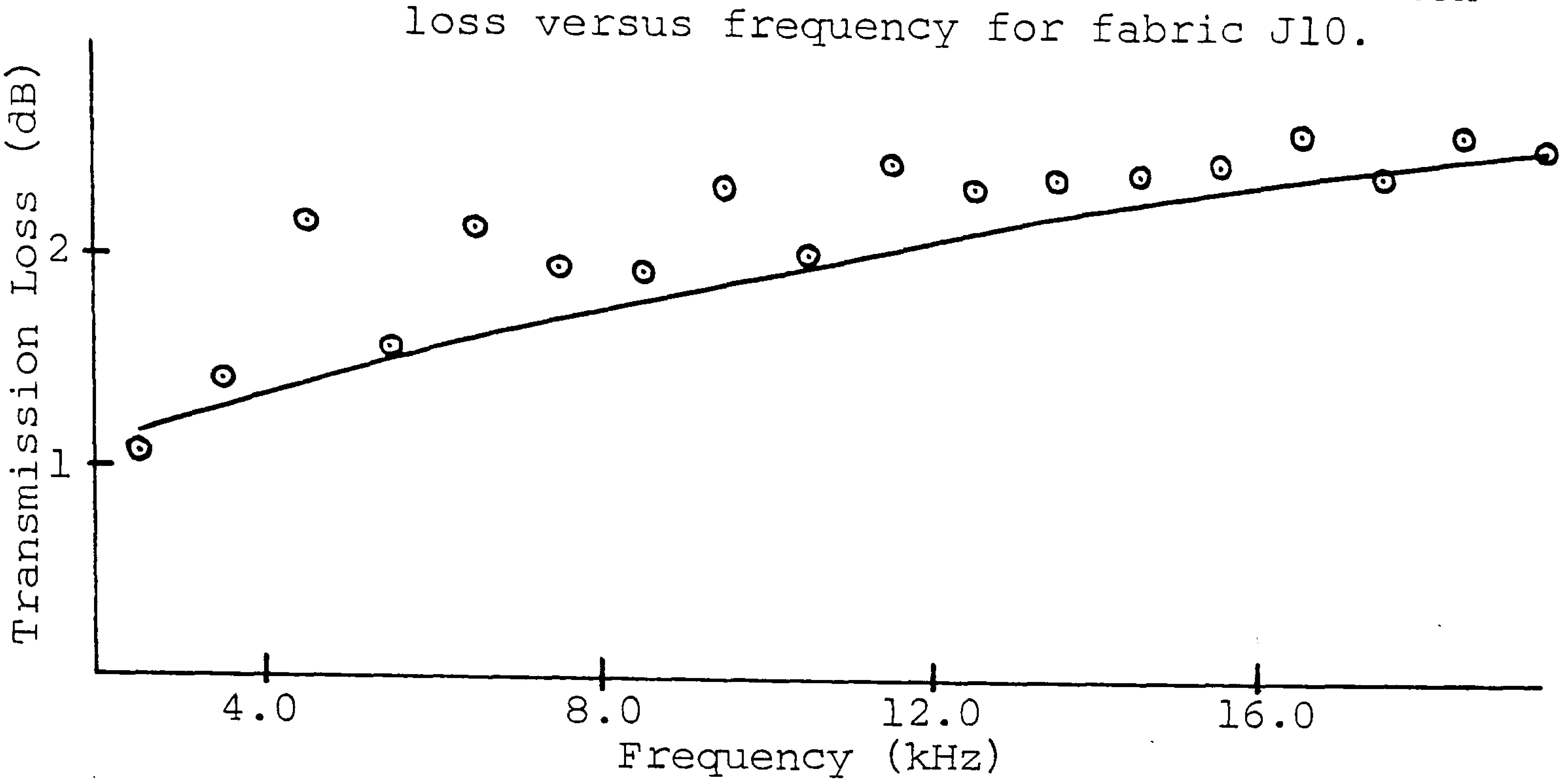


Figure A2.120 Experimental and theoretical transmission loss versus frequency for fabric J11.

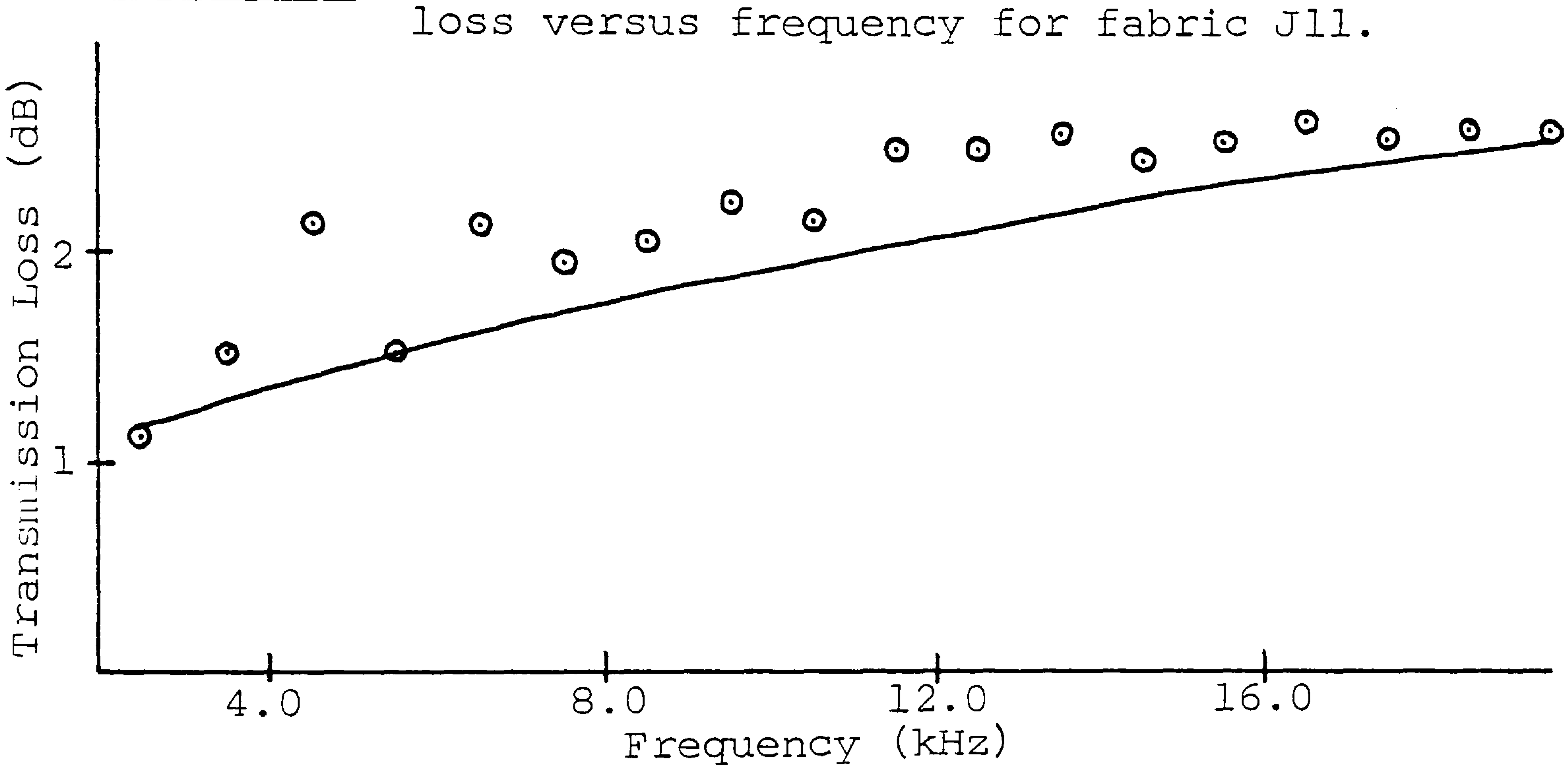


Figure A2.121 Experimental and theoretical transmission loss versus frequency for fabric J12.

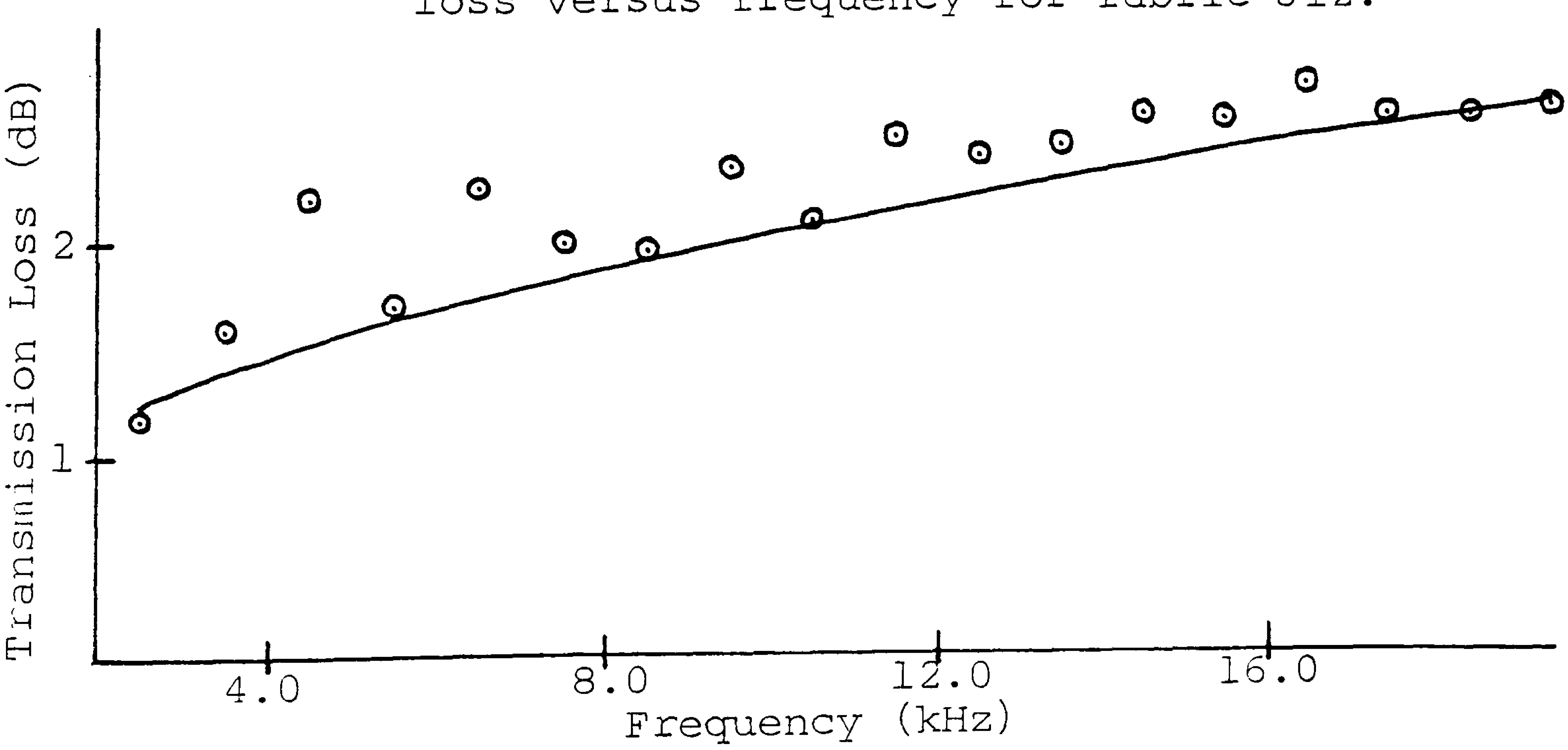


Figure A2.122 Experimental and theoretical transmission loss versus frequency for fabric J13.

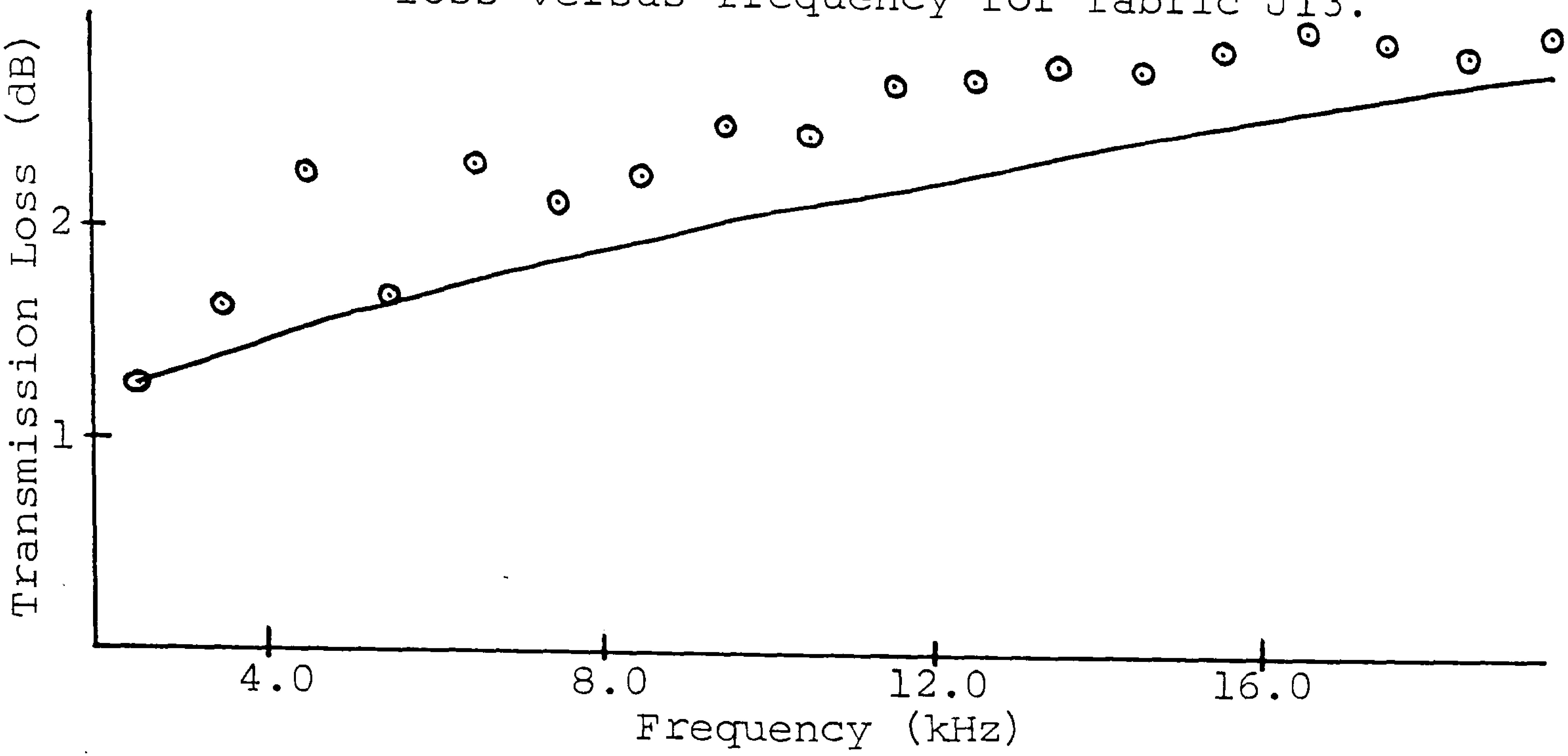


Figure A2.123 Experimental and theoretical transmission loss versus frequency for fabric J14.

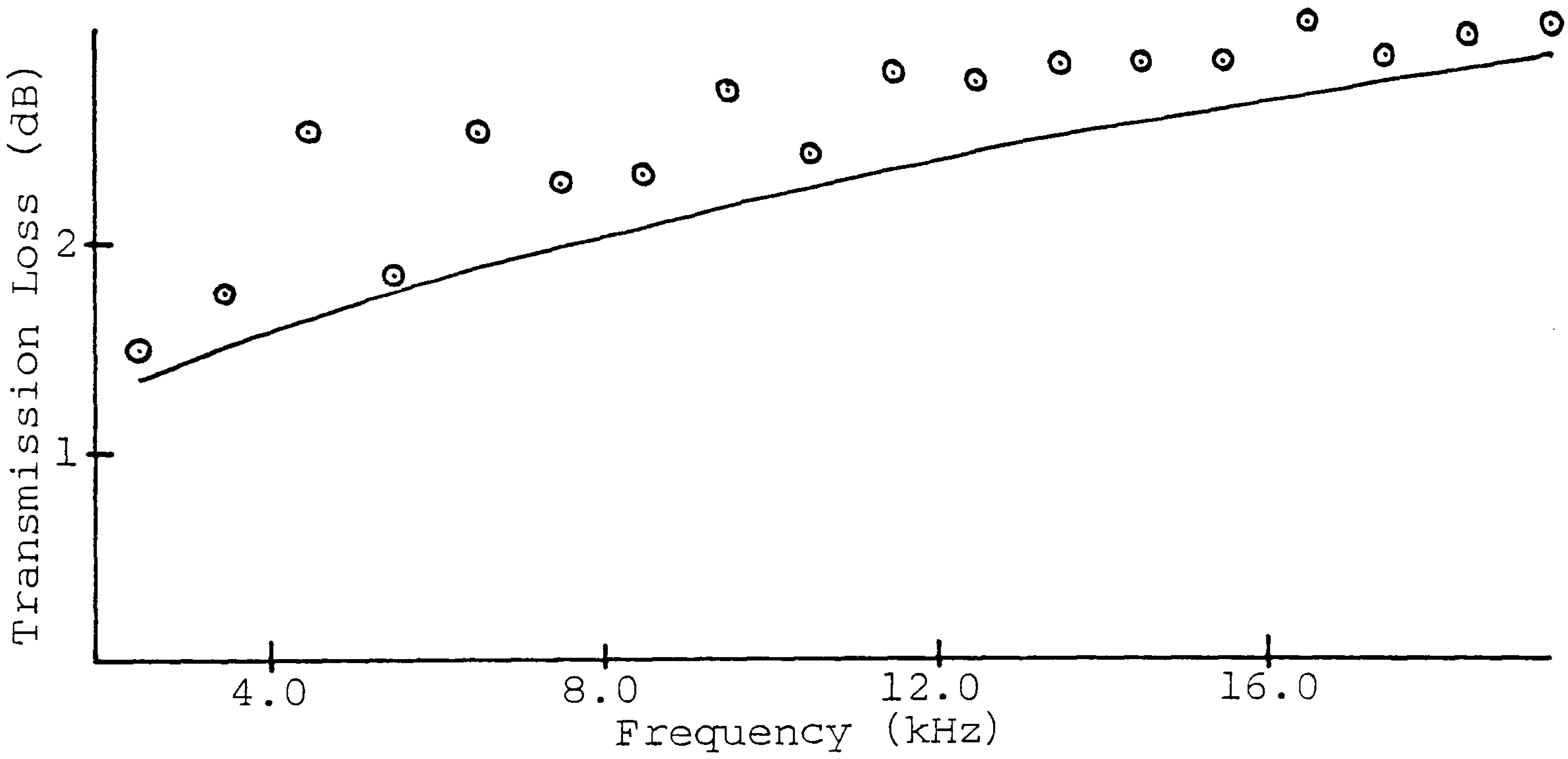


Figure A2.124 Experimental and theoretical transmission loss versus frequency for fabric J15.

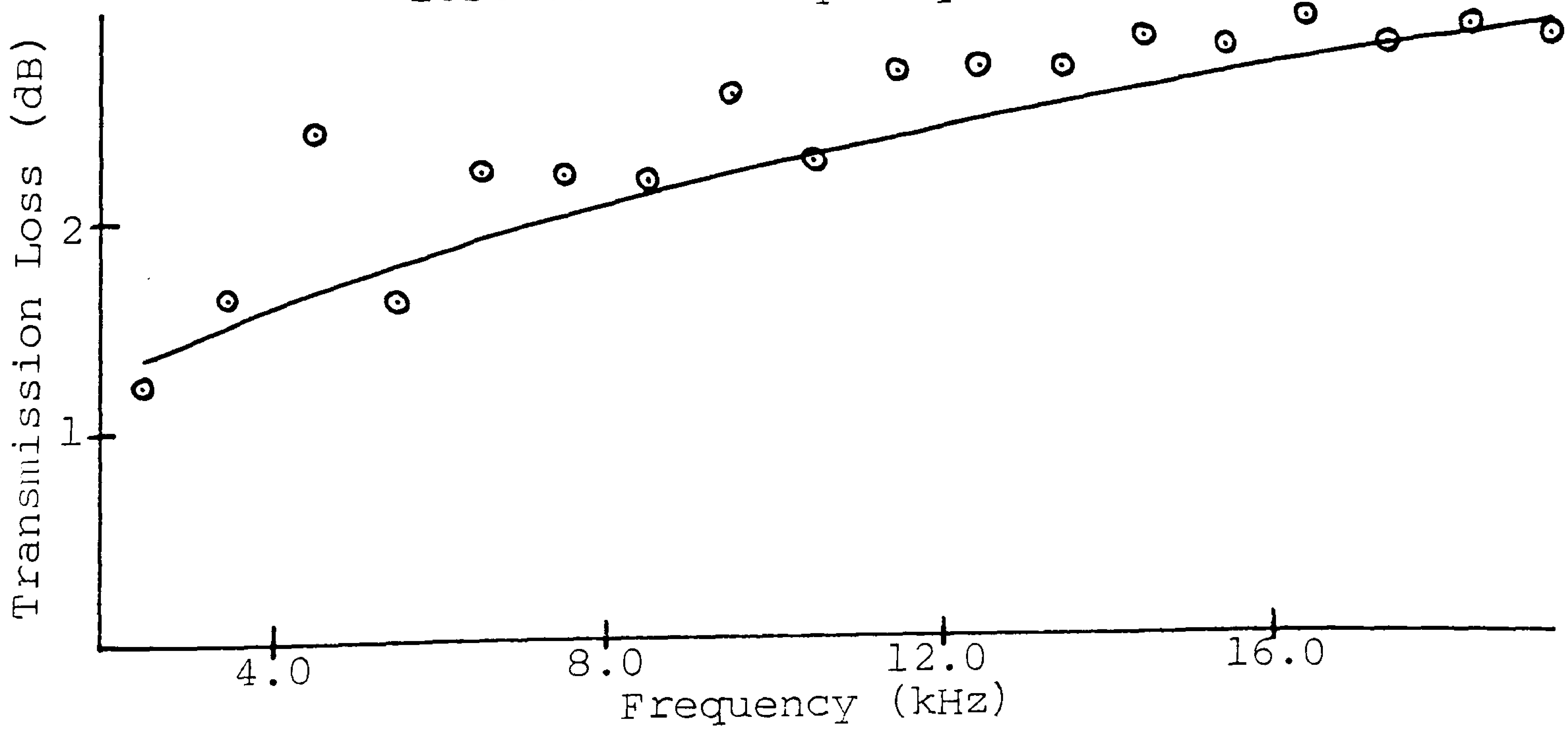


Figure A2.125 Experimental and theoretical transmission loss versus frequency for fabric K1.

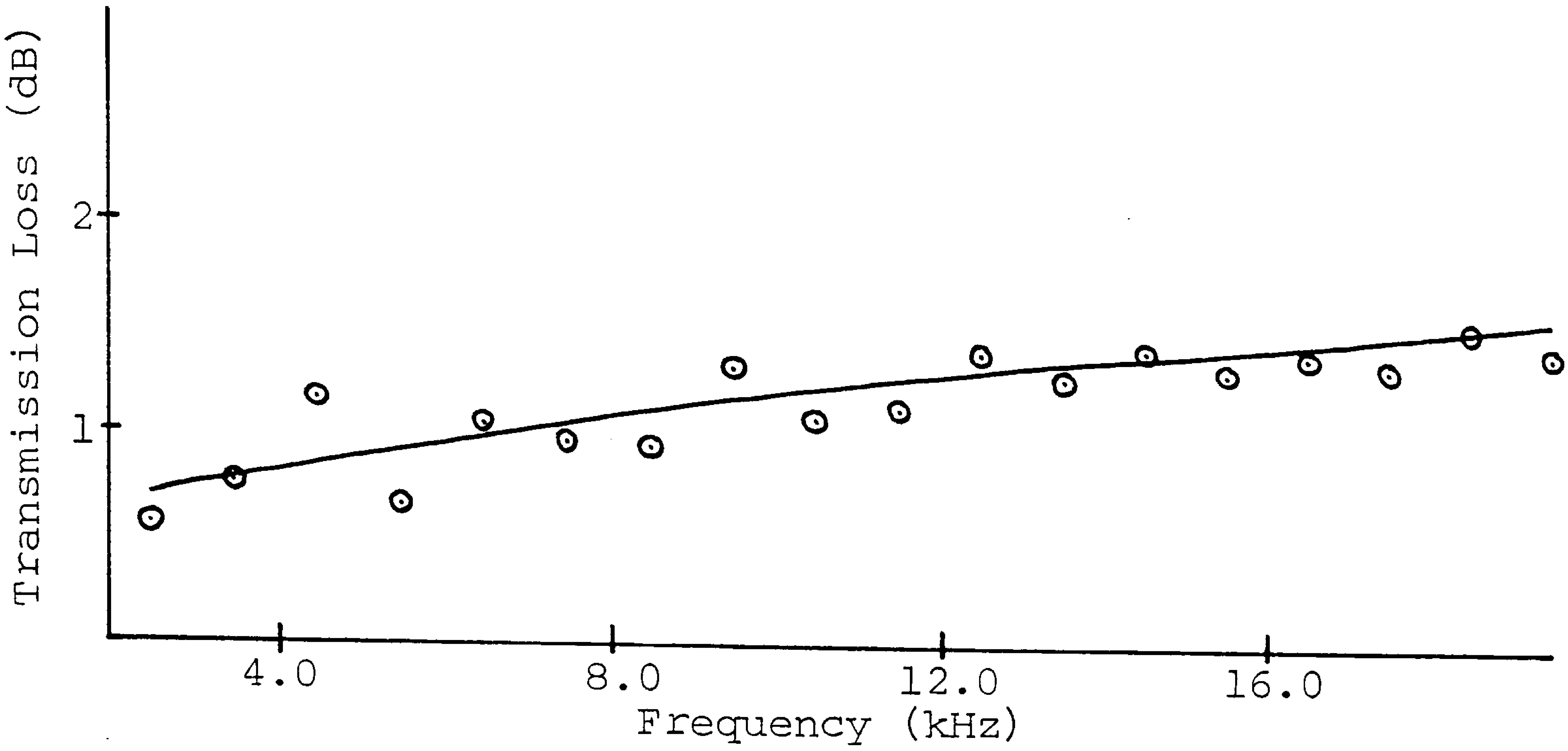


Figure A2.126 Experimental and theoretical transmission loss versus frequency for fabric K2.

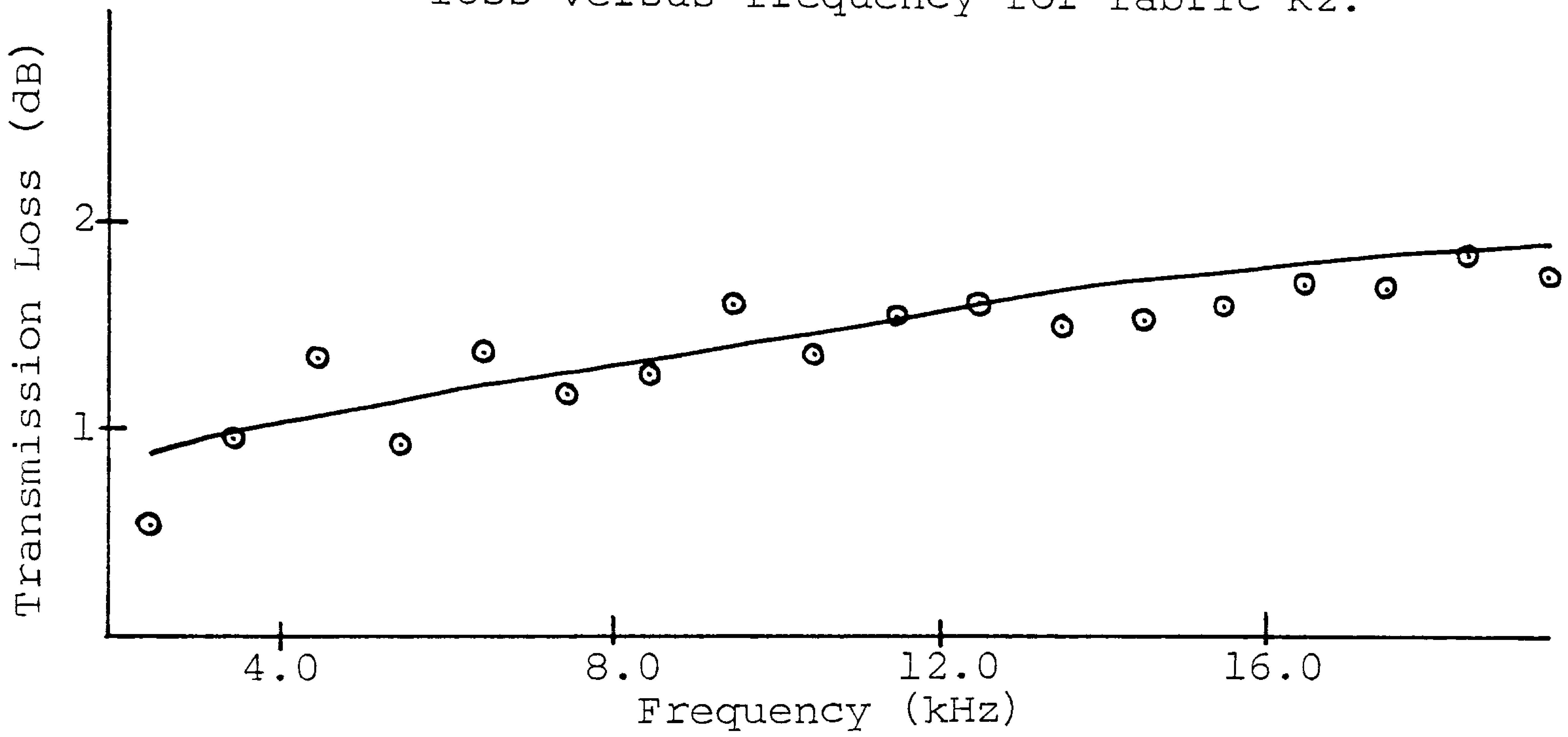


Figure A2.127 Experimental and theoretical transmission loss versus frequency for fabric K3.

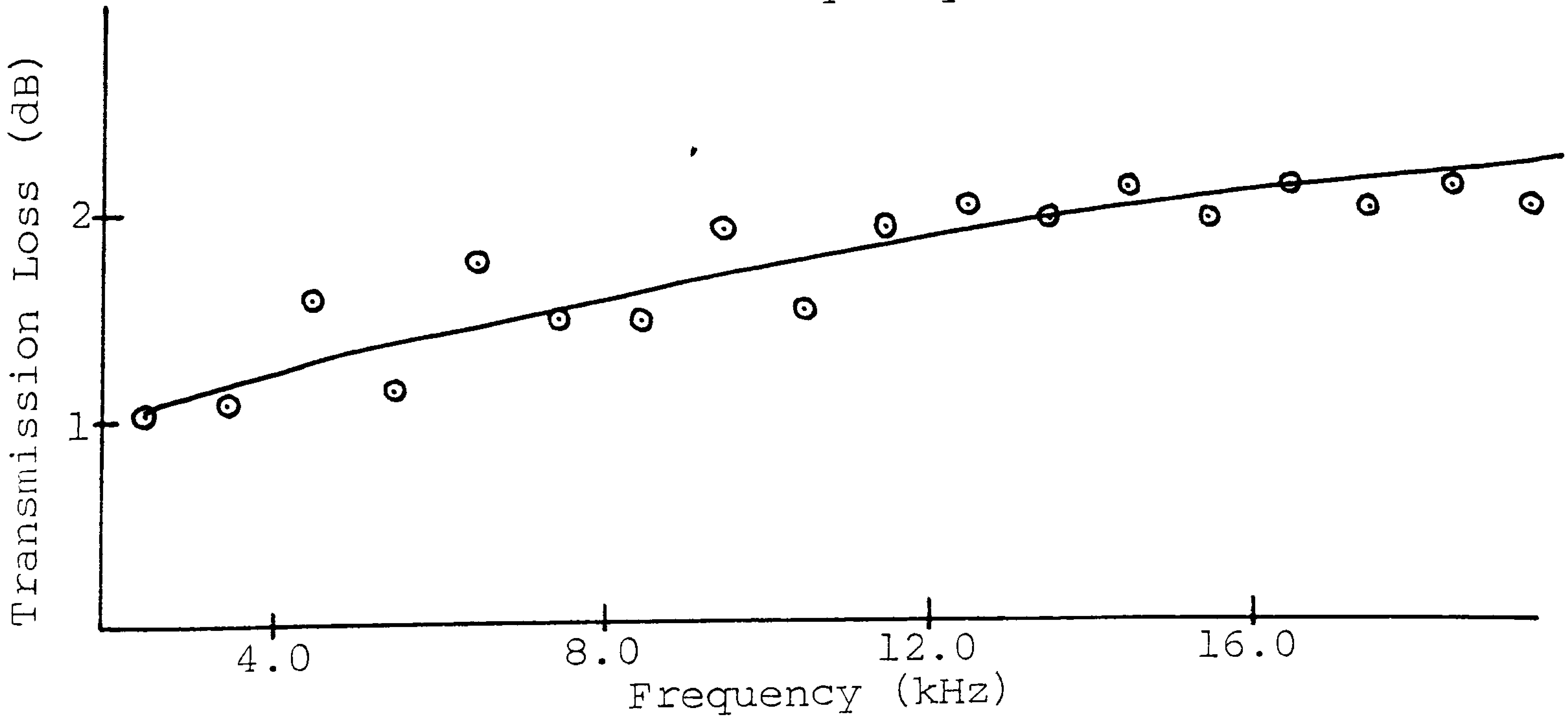


Figure A2.128 Experimental and theoretical transmission loss versus frequency for fabric K4.

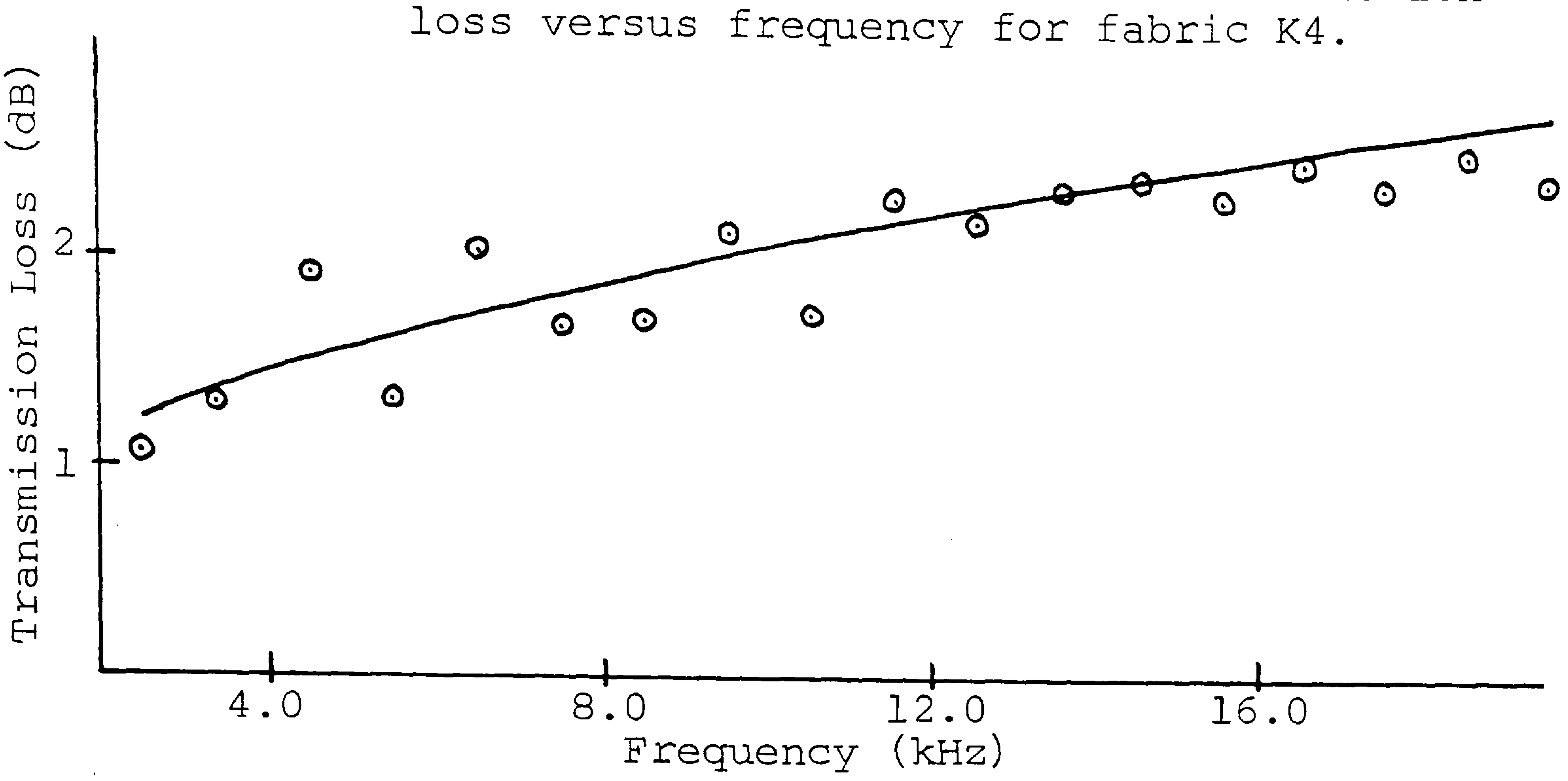


Figure A2.129 Experimental and theoretical transmission loss versus frequency for fabric K5.

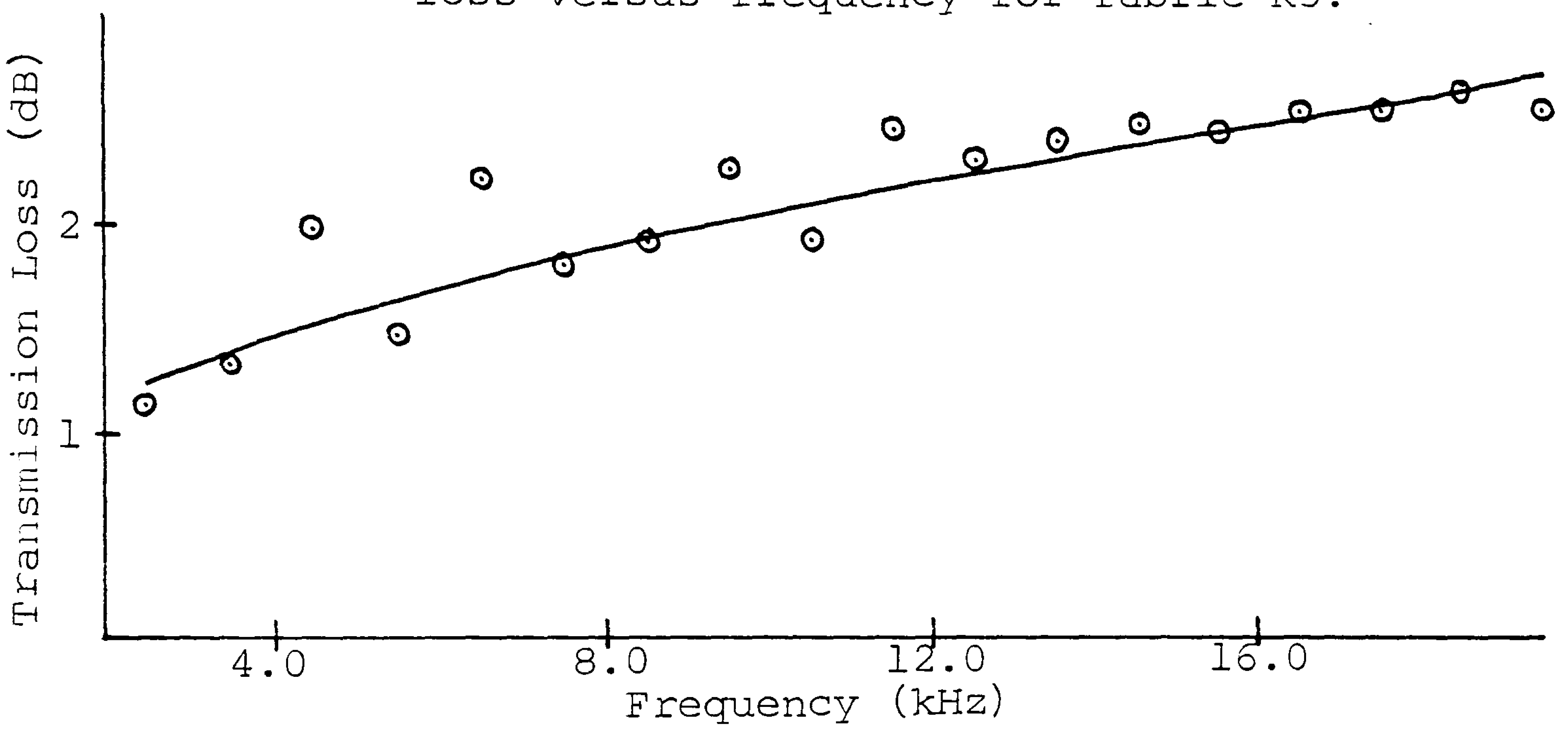


Figure A2.130 Experimental and theoretical transmission loss versus frequency for fabric K6.

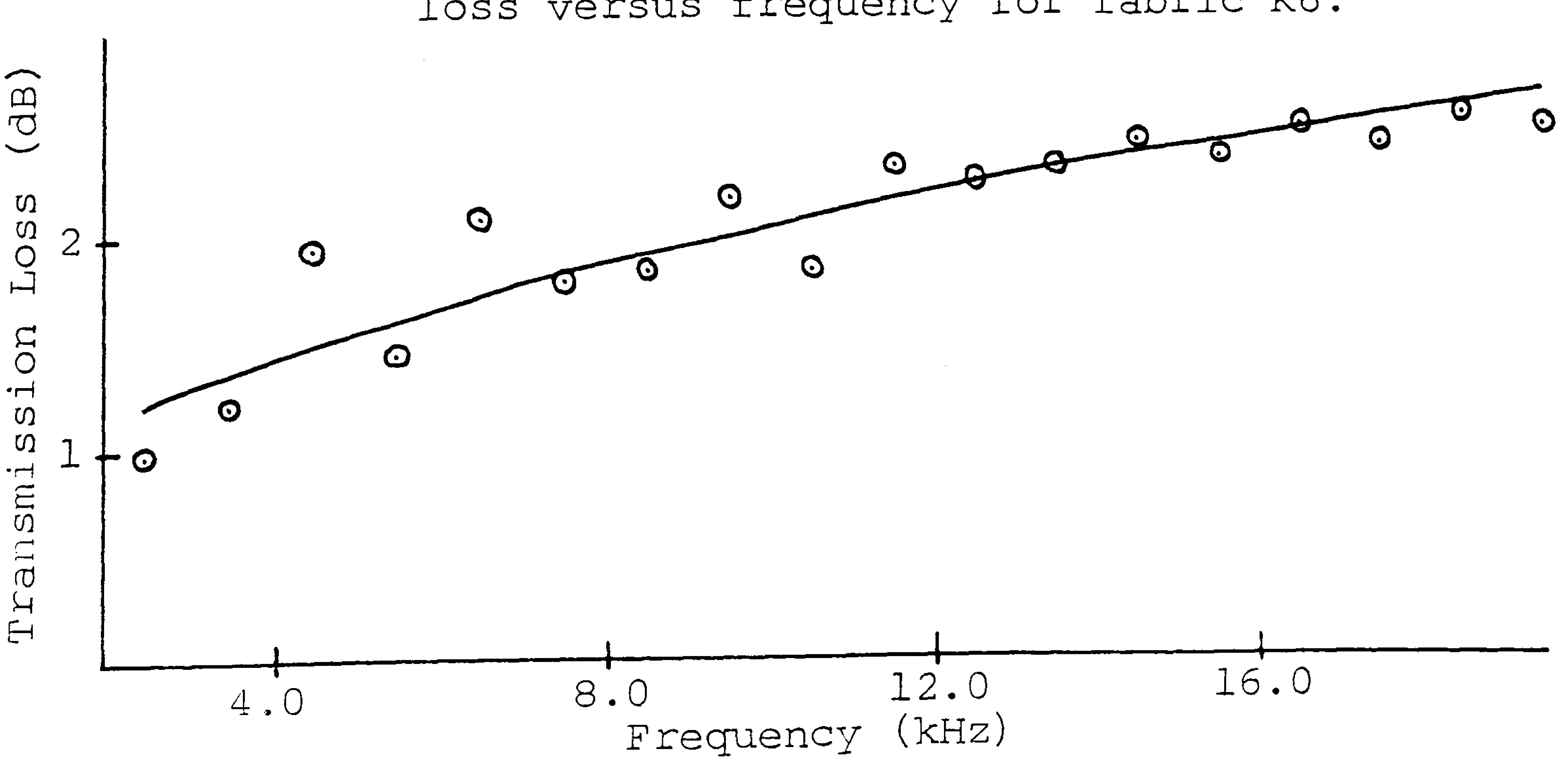


Figure A2.131 Experimental and theoretical transmission loss versus frequency for fabric K7.

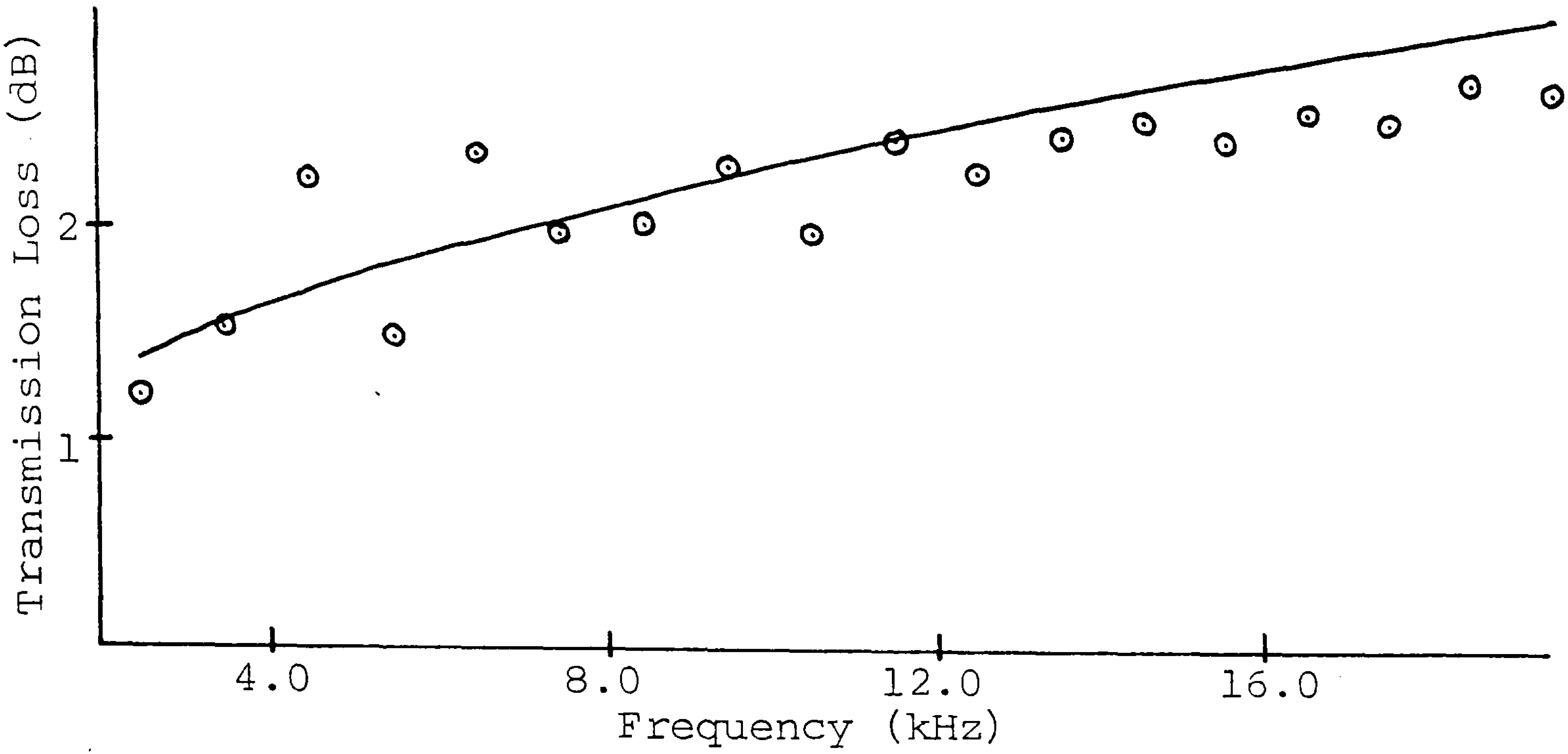


Figure A2.132 Experimental and theoretical transmission loss versus frequency for fabric K8.

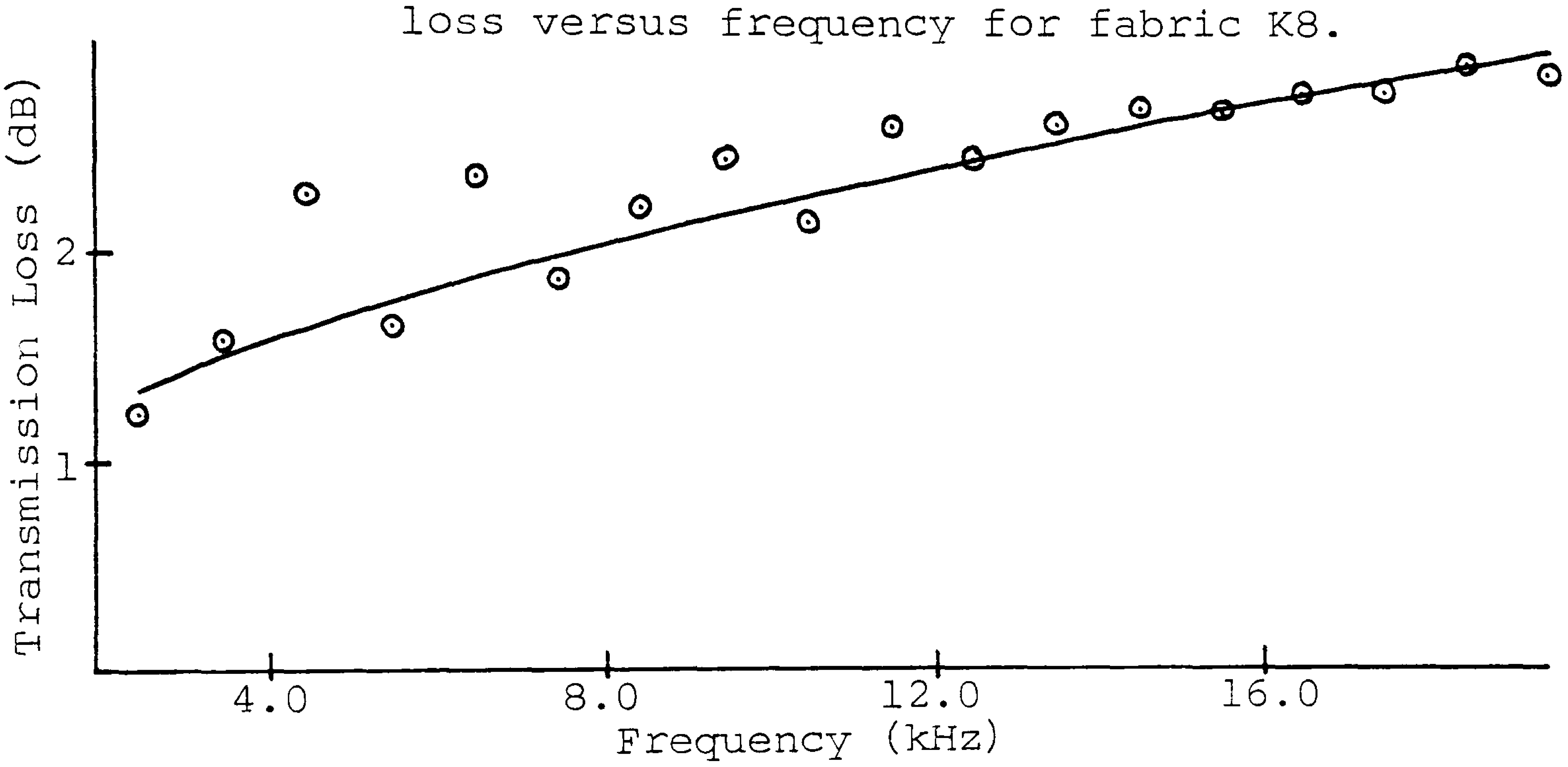


Figure A2.133 Experimental and theoretical transmission loss versus frequency for fabric K9.

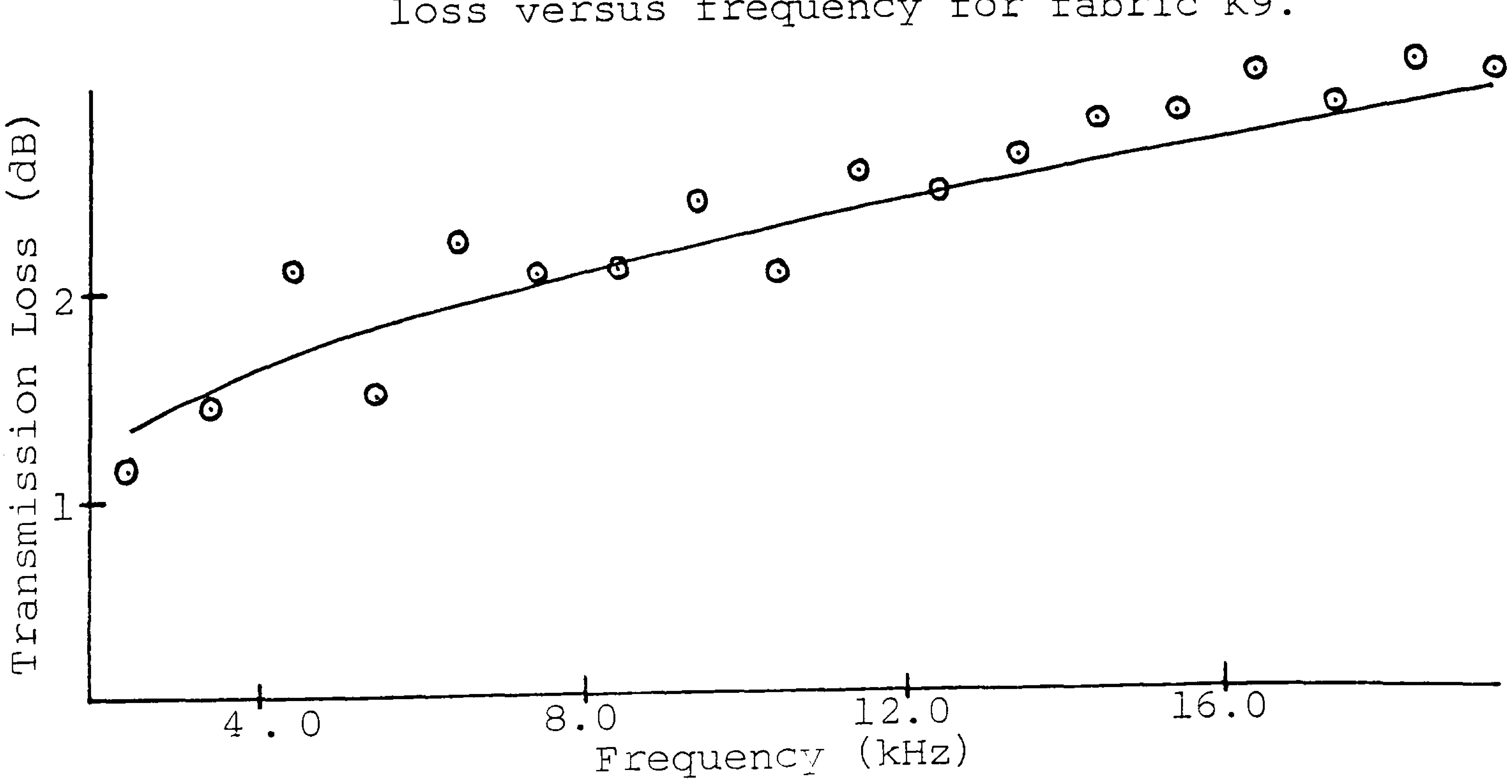


Figure A2.134 Experimental and theoretical transmission loss versus frequency for fabric L1.

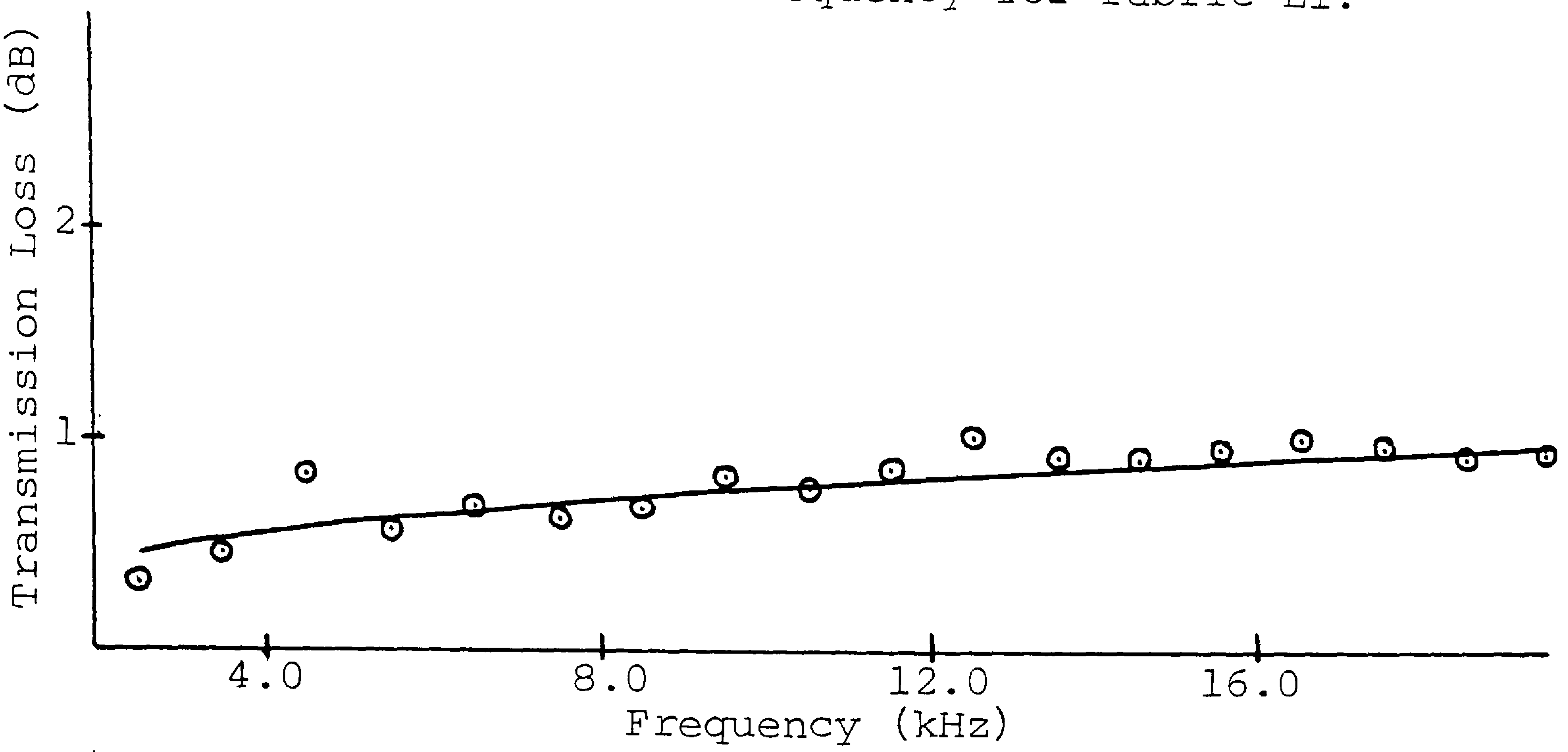


Figure A2.135 Experimental and theoretical transmission loss versus frequency for fabric L2.

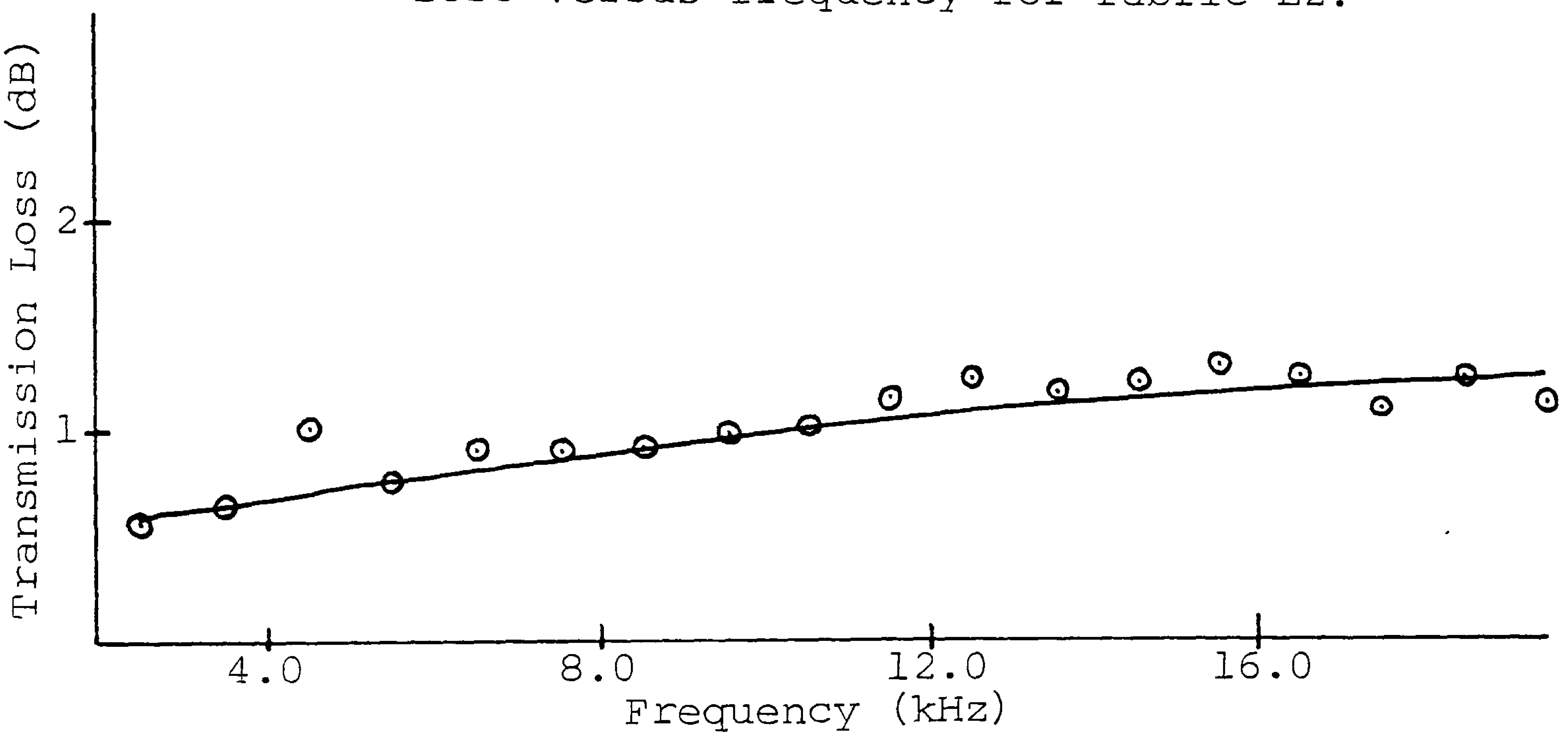


Figure A2.136 Experimental and theoretical transmission loss versus frequency for fabric L3.

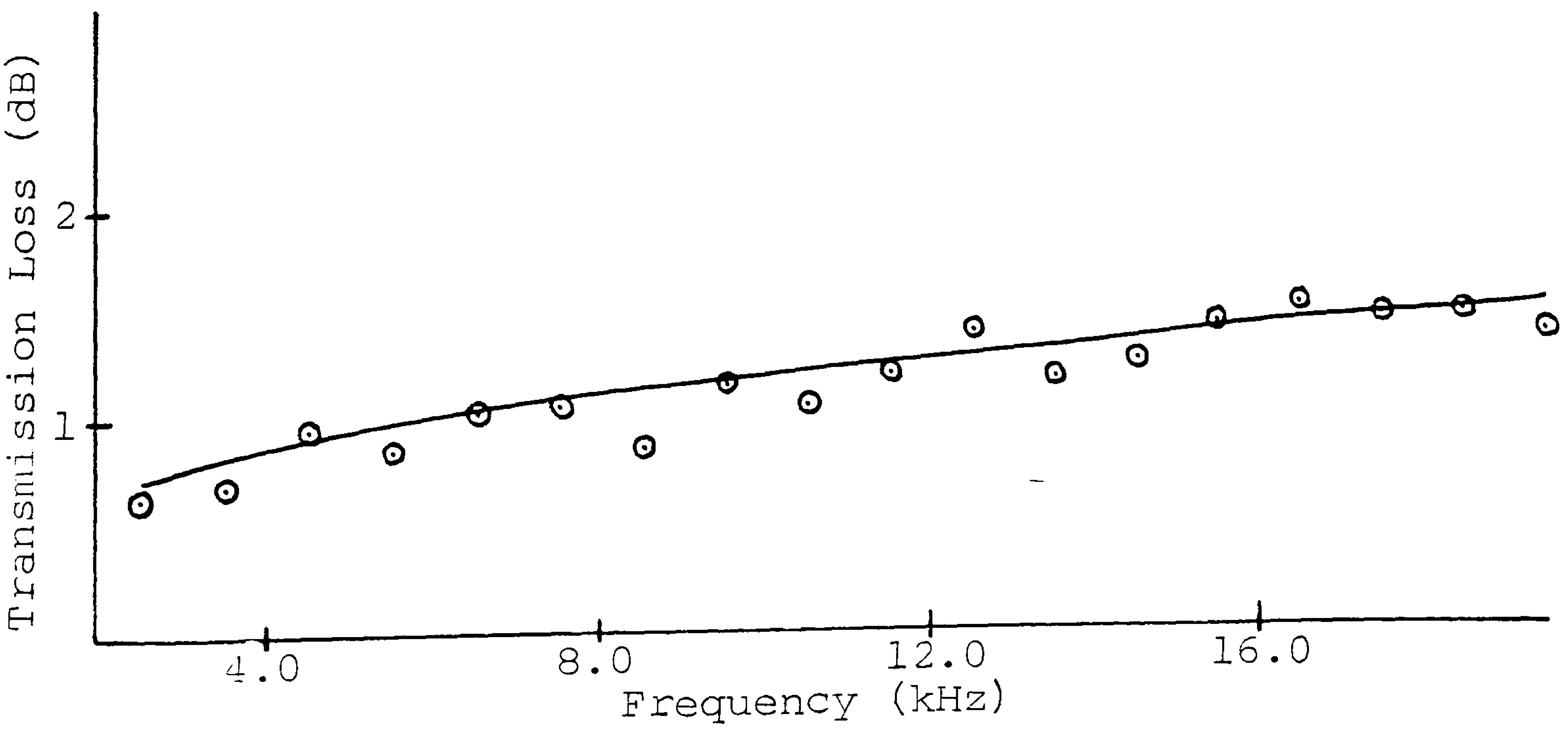


Figure A2.137 Experimental and theoretical transmission loss versus frequency for fabric L4.

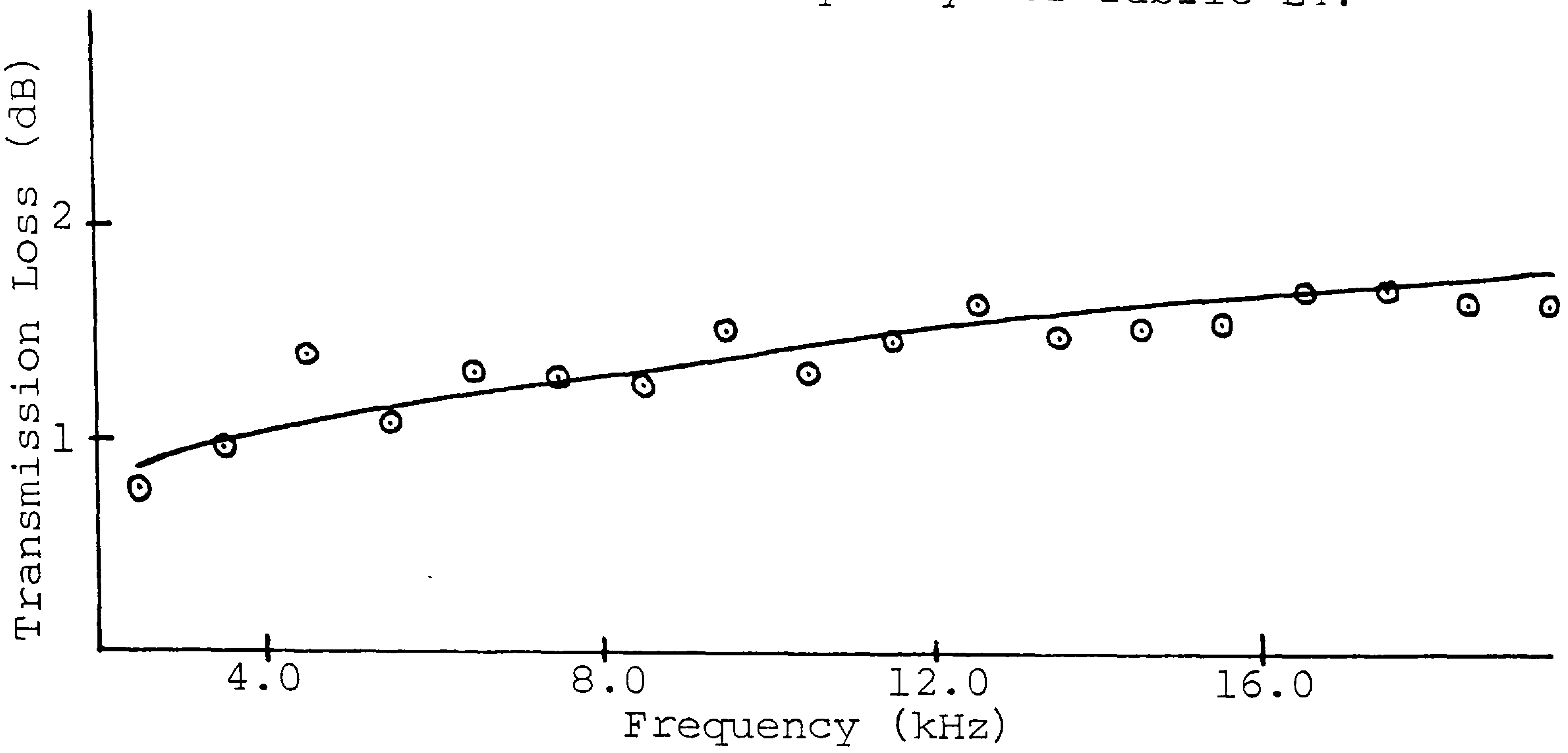


Figure A2.138 Experimental and theoretical transmission loss versus frequency for fabric L5.

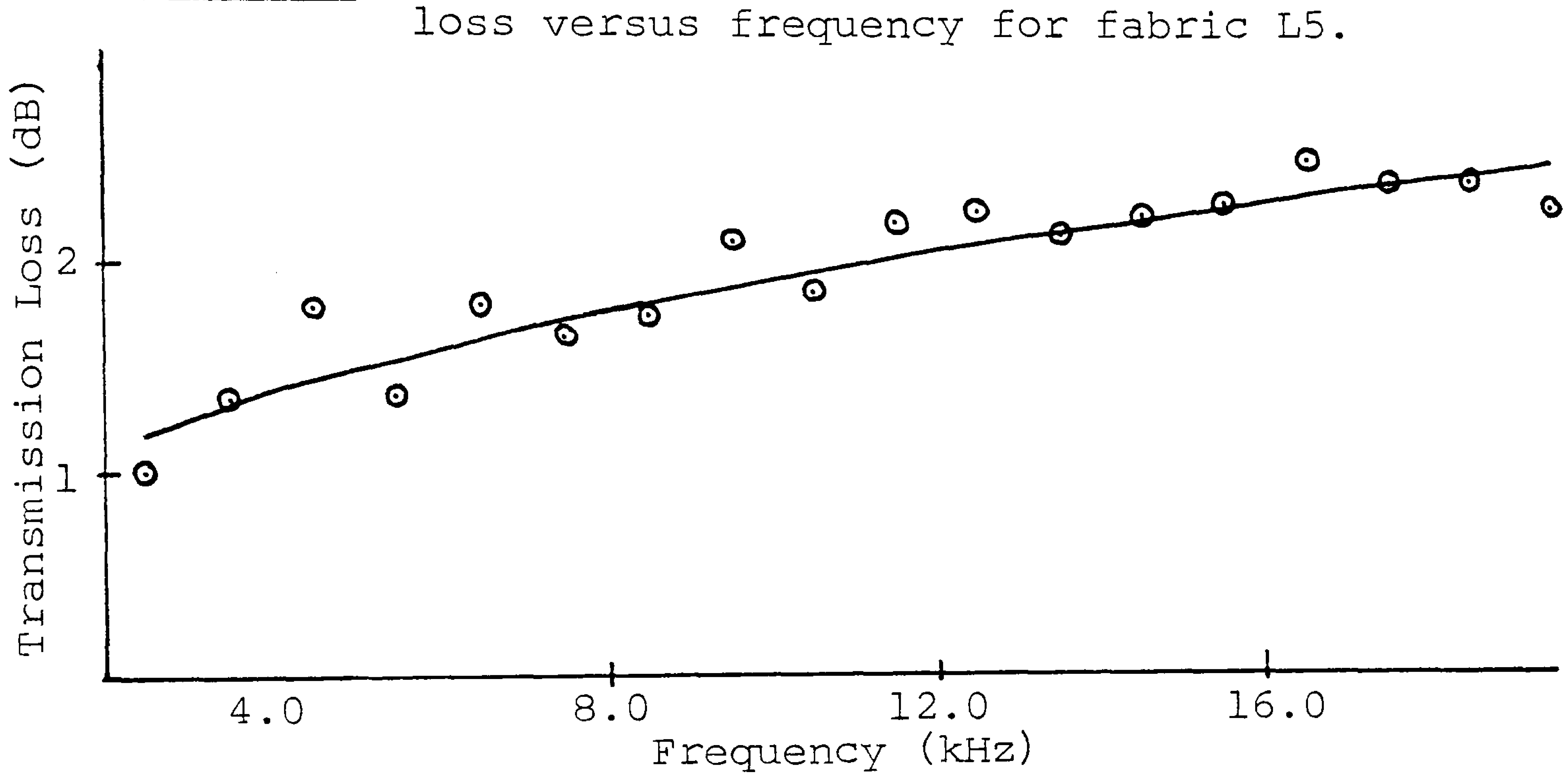


Figure A2.139 Experimental and theoretical transmission loss versus frequency for fabric L6.

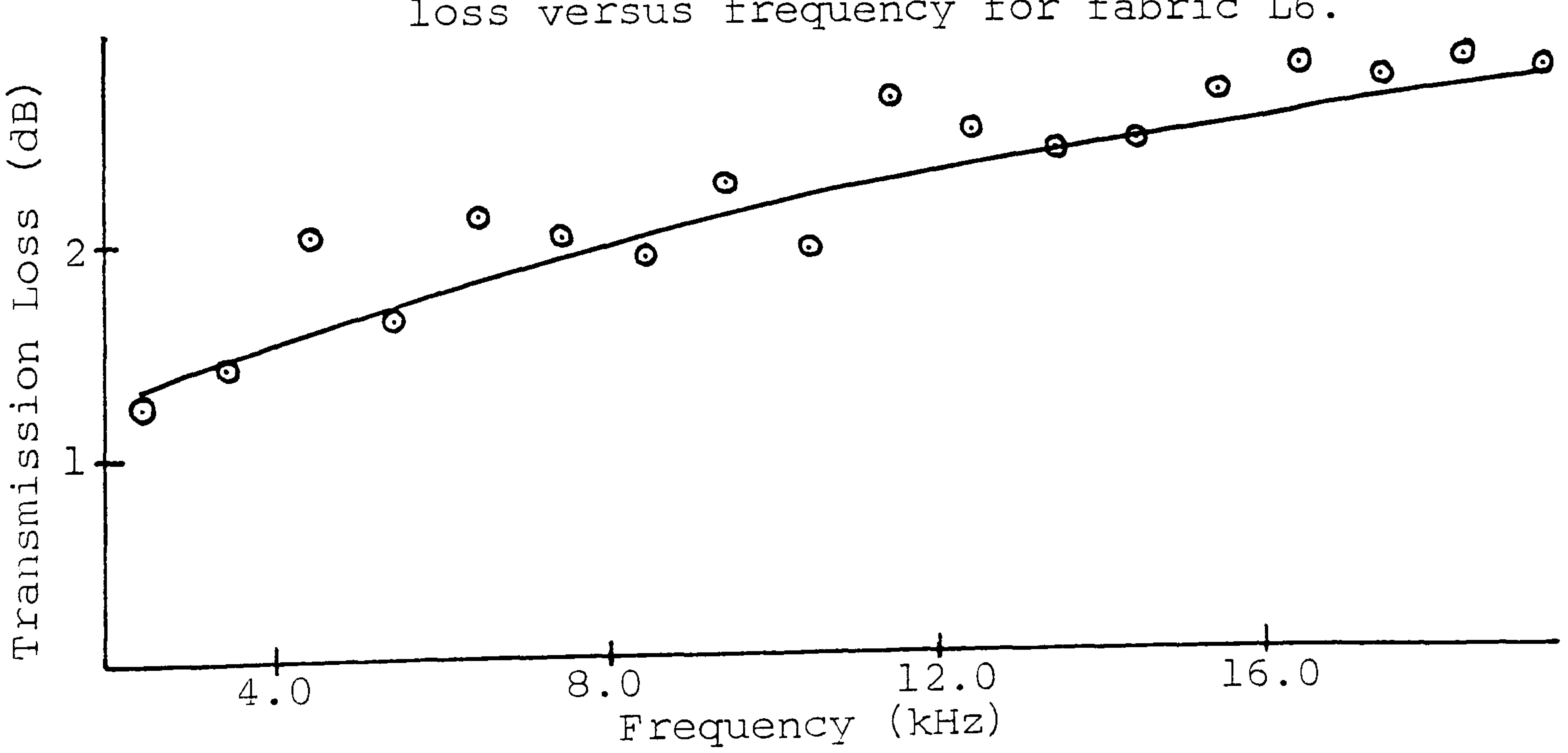


Figure A2.140 Experimental and theoretical transmission loss versus frequency for fabric L7.

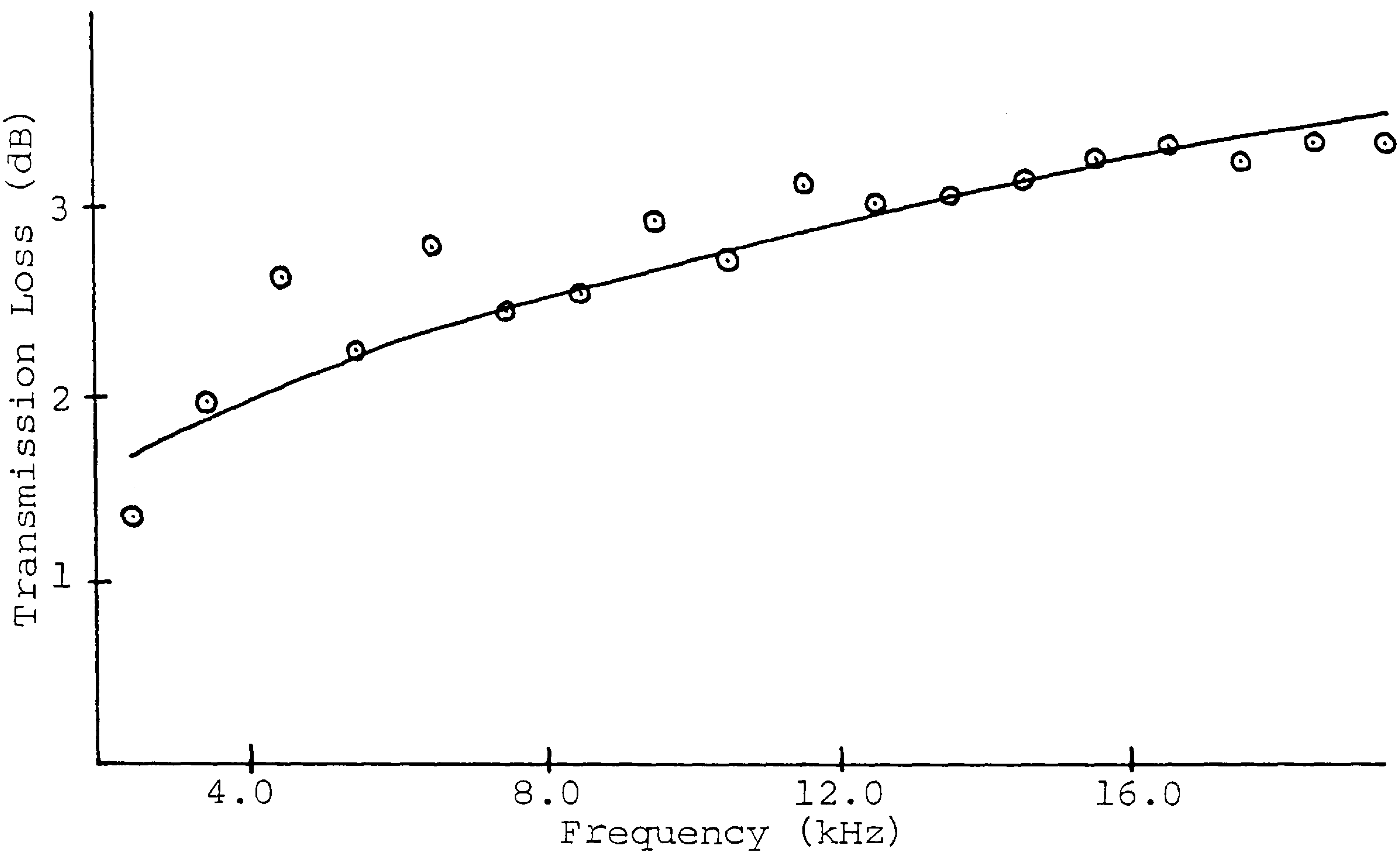
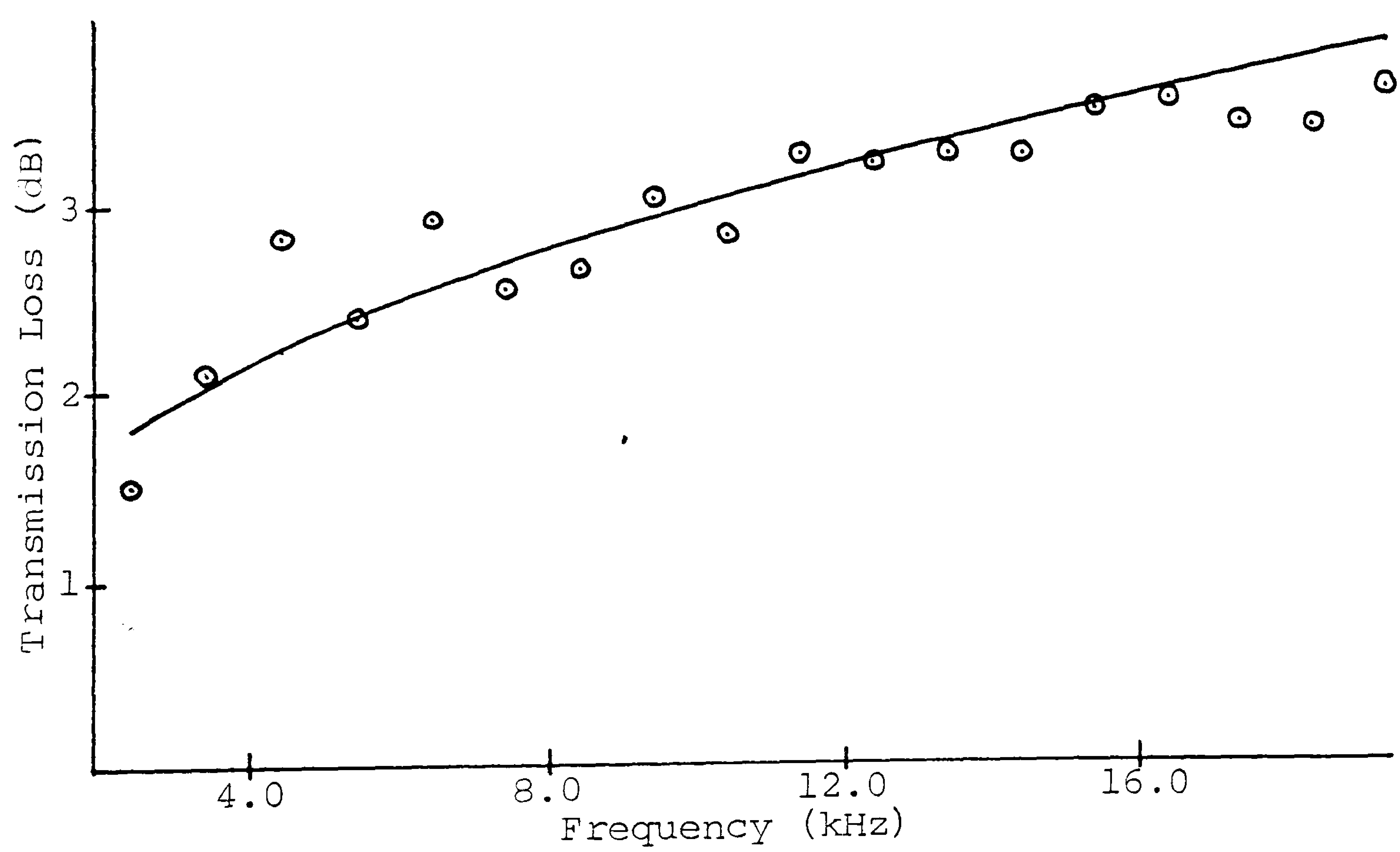


Figure A2.141 Experimental and theoretical transmission loss versus frequency for fabric L8.



APPENDIX THREE

CORRELATION BETWEEN EXPERIMENTAL AND CORRECTED THEORETICAL TRANSMISSION LOSS

Introduction

This appendix in the form of table A3.1 lists the correlation between the experimental and corrected theoretical transmission loss for all fabrics as discussed in chapter six, section two.

The correlation coefficient (r) was calculated using the standard formula

$$r = \frac{\sum_{i=0}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\left(\sum_{i=0}^{n} (X_i - \bar{X})^2 \sum_{i=0}^{n} (Y_i - \bar{Y})^2 \right)}$$

where:

X_i = ith. experimentally measured transmission loss.

Y_i = ith. theoretically calculated transmission loss.

$\bar{X}$ = Mean experimentally measured transmission loss.

$\bar{Y}$ = Mean theoretically calculated transmission loss.

n = Number of data points.

Fabric	Correlation Coefficient	Fabric	Correlation Coefficient
A1	0.87	C17	0.96
A2	0.90	C18	0.97
A3	0.90	C19	0.80
A4	0.89	C20	0.88
A5	0.87	C21	0.76
A6	0.88	C22	0.70
A7	0.83	C23	0.79
A8	0.83	C24	0.89
A9	0.90	C25	0.81
A10	0.90	C26	0.83
A11	0.90	C27	0.87
B1	0.80	C28	0.89
B2	0.92	C29	0.84
B3	0.92	C30	0.83
B4	0.92	C31	0.86
B5	0.92	C32	0.92
B6	0.94	C33	0.84
B7	0.91	C34	0.92
B8	0.93	C35	0.84
C1	0.94	C36	0.84
C2	0.94	D1	0.88
C3	0.97	D2	0.88
C4	0.94	D3	0.90
C5	0.94	D4	0.91
C6	0.99	D5	0.90
C7	0.98	D6	0.92
C8	0.97	D7	0.88
C9	0.96	E1	0.70
C10	0.97	E2	0.82
C11	0.97	E3	0.82
C12	0.98	E4	0.82
C13	0.98	E5	0.85
C14	0.95	E6	0.89
C15	0.99	E7	0.83
C16	0.94	E8	0.87

Table A3.1

Fabric	Correlation Coefficient
E9	0.88
E10	0.91
E11	0.88
E12	0.90
F1	0.92
F2	0.90
F3	0.93
F4	0.90
F5	0.94
F6	0.96
G1	0.85
G2	0.87
G3	0.94
G4	0.94
G5	0.92
G6	0.92
G7	0.95
G8	0.91
G9	0.95
G10	0.94
G11	0.96
G12	0.97
G13	0.95
G14	0.98
H1	0.89
H2	0.85
H3	0.93
H4	0.89
H5	0.91
H6	0.92
H7	0.94
I1	0.88
I2	0.87
I3	0.91
I4	0.91
I5	0.93
I6	0.93
I7	0.94
I8	0.95
J1	0.84
J2	0.89
J3	0.87
J4	0.90
J5	0.93
J6	0.94
J7	0.92
J8	0.89
J9	0.90
J10	0.88
J11	0.91
J12	0.89
J13	0.94
J14	0.95
J15	0.90
K1	0.87
K2	0.90
K3	0.90
K4	0.90
K5	0.91
K6	0.91
K7	0.89
K8	0.91
K9	0.93
L1	0.90
L2	0.89
L3	0.94
L4	0.91
L5	0.93
L6	0.94
L7	0.93
L8	0.92

Table A3.1 (continued)